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Pyrometers and Pyrometry

A GENERAL DISCUSSION

HELD BY

The Faraday Society

Faraday Society

Pyrometers and Pyrometry.

A General Discussion.

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PYROMETERS AND PYROMETRY.

A GENERAL DISCUSSION.

At the Meeting of the Faraday Society held on Wednesday, November 7, 1917, in the House of the Royal Society of Arts, John Street, Adelphi, London, W.C., a **General Discussion** took place on "**Pyrometers and Pyrometry.**" In the absence of the President **Sir Richard Glazebrook, C.B., F.R.S., Past-President,** occupied the Chair.

The proceedings were opened by the Chairman at 5.30 p.m. with the following Introductory Address:—

INTRODUCTORY ADDRESS ON "PYROMETERS AND PYROMETRY."

By Sir RICHARD GLAZEBROOK, C.B., F.R.S.

I am here by a set of circumstances which I very much regret and which I am sure all the members and visitors will regret. The original arrangement for this meeting had been that our President, Sir Robert Hadfield, at whose suggestion the discussion is being held, would preside, and we had looked forward to hearing his contribution to the discussion. We are indebted to him at every turn for his enthusiasm in the subjects that are dealt with at our meetings, for his great practical interest in the work of the Society and, indeed, all scientific work bearing on the problems that concern the objects of the Society. We value the manner in which he realizes the importance of scientific investigation and the support that he has always so consistently given to research for industrial objects, while at the same time he has shown a wise appreciation of the importance of investigations in the realm of pure science. For all these reasons I am sure you regret that he is unable to be present. For myself, I can only hope to replace him very feebly indeed. I do not propose to give you an introductory address, at any rate at any length, but there are a few remarks that I should like to make with regard to the subject and with which I will trouble you for a few minutes.

My own personal interest in the subject is, I think, chiefly scientific, from the point of view of the scientific measurement of high temperature and the investigation of the effect of high temperature on materials of all kinds. I go back in memory to the early days of the National Physical Laboratory when we commenced to consider not the measurement of the high temperatures that we are to deal with this evening but the measurement of temperatures within the ordinary normal range of working. In those days the laboratory had a very generous and keen supporter in Sir Andrew Noble, and I remember well his horror when he was told that we had no means of

measuring temperature as regular organized work in this country beyond the range of the old Kew thermometer. One of the first pieces of work he set us to do at the laboratory—and which he supported by his own well-known generosity—was to investigate the relation between the air thermometer and the platinum resistance thermometer which a few years previously had been introduced and studied so largely by Professor Callendar over a range up to possibly 1,200° C. That was one of the first pieces of work undertaken by Dr. Harker, who was then almost the only assistant at the laboratory. In those days, and still over the range of temperature between 0° C. and 100° C., we looked to the work of the Bureau International at Sèvres, the work of Bênoit, Guilleaume, and Chappuis which had established that scale of temperature, and had shown within limits of high accuracy its relationship to the thermodynamic scale. That was the scale that we adopted, of course, and to which our standards were referred, but the Bureau International were chiefly concerned with the standardization of weights and measures, and in those days the measurement of high temperature did not come very fully within the scope of their investigations. Their interest in temperature work was to make sure of the temperatures at which their various lengths were measured and their weights standardized, and it was only in the year 1913 that, urged by the efforts of the late Sir David Gill and Professor Stratton, of the Bureau of Standards, Washington, that the Bureau International undertook to go into the question of the standardization of higher temperatures. At the fifth meeting of the Conference on Weights and Measures held in Paris in October, 1913, the Conference passed some important resolutions dealing with their own relation to the standardization of higher temperatures, and it was to be the work of the national laboratories represented at the conference to endeavour in the course of the next few years to turn into practical methods of measurement the resolutions that were then adopted. Accordingly correspondence took place between myself in England, Dr. Warburg, of the Reichsanstalt, and Dr. Stratton, of the Bureau of Standards, and a good deal of preliminary work was done in the hopes of introducing an international scale of high temperature, at any rate for temperatures up to 1,000°, 1,200°, or 1,300°, and, we hoped, beyond that. Representatives of the Reichsanstalt visited the National Physical Laboratory and proposals and schemes were considered and discussed; it was arranged that a conference should be held in Berlin to settle the whole matter, the date fixed for the beginning of the conference being September 25, 1914. Dr. Stratton's last letter to me dealing with the matter was dated July 30, 1914; he then wrote, "I am looking forward with pleasing anticipation to meet you at the Berlin conference." Events have proved otherwise, and the Berlin conference has never taken place. Correspondence, however, went on between the Bureau of Standards and the Laboratory, and a series of resolutions were accepted both by the Bureau of Standards and ourselves which are referred to in Mr. Griffiths' Paper, one of the first to be read to-night, and which are contained in this pamphlet which I have here, a pamphlet dealing with the standardization of thermoelectric apparatus and with pyrometry at the National Physical Laboratory. One outcome of that work has been to establish a certain fixed point scale giving fixed points of temperature up to 1,083° C., the melting-point of copper in a reducing atmosphere, and that, I think, is adopted now in America and England as the practical scale of temperature for at any rate the lower range of temperatures that we are dealing with this evening. It is clear, however, from the papers to be read that that scale is insufficient; much higher temperatures are dealt with and have to be considered.

As to the importance of the problem, I need hardly say anything. Illustrations occur in every direction. A few are sufficient to enforce the point. In our experience at the National Physical Laboratory we not infrequently come across difficulties of a metallurgical character that obviously are due to uncertainty in the measurement of high temperatures. A method of treating steel, it may be, or some other process by experimental work and careful investigation has been very clearly laid down, but when it comes to works practice then frequently rules that are the result of laboratory experience are found difficult to follow exactly; free methods that are possible in the works need, I feel sure you will agree, further and more complete development; it is the object of the papers that deal with the metallurgical side of the subject to endeavour to show us how these difficulties can best be met.

Let me mention perhaps one instance which happened not so long since. We were asked to suggest a proper method of treatment of a steel for certain apparatus which was urgently required, and it appeared clear from the investigation as to what exactly the treatment should be. Arrangements were made for manufacturing the articles carrying that treatment out, and—I am speaking from memory—when they were completed 40 or 50 per cent. were rejected. It then remained to investigate what was the cause of that rejection. It had been clearly pointed out that accuracy in measuring the temperature at which the steel was quenched was of the utmost importance, but when inquiry was made it was found that the articles were heated in an ordinary smith's forge and quenched at a temperature that a skilled workman thought was the right temperature. I have the utmost respect and regard for the skilled workman. Much of our present prosperity is due to the excellence of his work, but clearly I think the time has gone by when it is sufficient to trust to the eye and experience of any skilled workman for the accuracy that is needed in dealing with metallurgical processes of this kind.

I trust that one of the results of this large meeting and of the discussion that is to take place will be to impress, not on the members of the Faraday Society, for I think they realize it already, but to impress generally on the English people the necessity, if we are to retain our place, still more if we are to advance our position, of applying the very highest and most carefully thought out results of scientific inquiry to all these complicated problems that come before us. With these few words I will open the meeting; we regret that Dr. Northrup is not here with us. You have had his communication circulated and I will ask the Secretary to read a very brief account of that.

The following communication to the discussion was received from the **President, Sir Robert Hadfield, F.R.S.**, subsequent to the meeting.

It was with great disappointment that I could not be present at this interesting and important Symposium, but I have pleasure in sending a bibliography on pyrometers (see pp. 160–170) which I have had prepared, and I hope it may be of service. Whilst not necessarily containing all records, this has been made as complete as possible. It also includes references since about 1889 to pamphlets, papers, and cuttings on this subject, including the title of the paper, author's name, and where published, also British and foreign patents.

I may mention that the first pyrometer used by my firm, Messrs. Hadfields, Ltd., Sheffield, was obtained through Professor Henri le Chatelier, to whom the world owes a great debt of gratitude for the important work he has done in connection with this subject. I have suggested that our Society send a special message to him, expressing our profound admiration for the great success of his life-long work in connection with his development and improvements of apparatus for accurately determining high temperatures—a study he has made his own—as well as in many other branches of science and its practical applications.

It is interesting to note that Professor H. le Chatelier, in his letter of February 10, 1891, hardly thought the electric pyrometer could be used by workmen. He was quite right, but matters have now greatly advanced, and the best type of educated workman can now be taught to make practical use of Le Chatelier's great aid to the metallurgist, and to know correctly the temperatures used in various industrial operations. I had previously been in touch by correspondence with the maker of the pyrometers, Messrs. J. Carpentier, in 1890.

It should be here mentioned that one of the first papers on the practical application of pyrometry to industrial uses was read in 1890 by Monsieur Emilio Damour, entitled "Sur la Mesure des Températures élevées, dans l'Industrie, et sur le Pyromètre thermoélectrique de M. le Chatelier." Professor H. le Chatelier was then Engineer-in-Chief of the Corps des Mines and Professor of Chemistry at the Ecole des Mines.

The first Le Chatelier electrical pyrometer with which I came in touch was supplied to my firm through Messrs. J. Carpentier, of Paris, in April, 1890. This performed excellent service in our works until 1900, when we obtained the first British-made pyrometer, manufactured by Messrs. Baird and Tatlock, of Glasgow, from whom we eventually ordered a dozen of these instruments at a cost of about £12 each. These

served their purpose excellently until they gave way to more accurate apparatus made by Messrs. J. Carpentier, of Paris. One advantage of the instrument made by Messrs. Baird and Tatlock, which no doubt enabled us to make use of it in a practical way, was that it was portable, which was not then the case with the Le Chatelier one. Messrs. Baird and Tatlock, who of course worked on the lines of Le Chatelier's discoveries, were the first British firm to try to meet technical and practical requirements in this country for apparatus used in connection with pyrometry, and credit should be given to them for this. In the early days of pyrometers they were one of the few firms of instrument makers who took a great deal of trouble, often with but little sympathy and help from the user, in endeavouring to arouse interest and attention with regard to this subject, which is now of the greatest possible importance to all those who handle ferrous, non-ferrous, and other materials in which exact knowledge of the temperatures to which they are subjected is necessary. The extraordinary differences brought about, specially in ferrous products, by variation in temperature of even only a few degrees, was never properly understood until the aid of pyrometers became available.

My firm also tested the Callendar instrument and the Le Chatelier optical pyrometer, but did not adopt these. Apparently we regarded this Le Chatelier instrument as giving accurate results, but as being rather delicate and troublesome to use. Nowadays, of course, we recognize that pyrometers cannot be used without a great deal of attention.

In 1901 we purchased our first recording pyrometer, the Roberts-Austen instrument, from Messrs. J. Pitkin & Co. This proved an excellent instrument and is still in use.*

In conclusion, I am glad to find that my suggestion to the Council of the Faraday Society to have a Symposium on this important subject has resulted in the holding of such a successful meeting. The presentation of so many valuable papers, not only from those in this country but also from some American friends of mine whom I persuaded to contribute, must prove of great benefit to metallurgists and others.

I should like to call attention to the contribution sent by Mr. S. A. Main, B.Sc. (pp. 111 and 158), who superintends the pyrometrical work in the Research Department of my firm, and believe it will well repay perusal by those interested in this important subject. In the statement, Mr. Main reviews pyrometry in its general application, thermoelectrical pyrometers, optical and radiation pyrometers, Brown's control pyrometers, and others. Mr. Main has evolved an excellent calibration chart, facilitating the calibration of optical pyrometers; I believe this will be found a most useful method, and full credit is due to him for the manner in which he has worked this out.

I was glad that my efforts to obtain papers from America on this subject proved successful, specially at a time when our cousins over the water are so pressed, as shown by the excellent contributions submitted by Dr. E. F. Northrup, of the Palmer Physical Laboratory, Princeton, N.J., and Mr. Richard P. Brown, of the Brown Instrument Company, Philadelphia.

* It is with much pleasure that I bear record to the excellent work done, and assistance rendered, by Dr. R. S. Whipple of the Cambridge Scientific Instrument Company and also by Mr. R. W. Paul.

Correspondence with M. le Chatelier.

Copy of Letter from Sir Robert Hadfield to Professor H. le Chatelier.

29th January, 1891.

I notice in the September number of the *Bulletin* of the Société d'Encouragement, p. 67, there is mention made of your report to the Council respecting experiments on the measurements of heat temperatures. Has any full copy of this paper yet been published? If so, I should like to have one.

We have ourselves made a few experiments with your pyrometer obtained from Carpentier, and find it the only one that gives an accurate idea of high temperatures. If it could be modified in any way to make it more easily handled by workmen, it would, I am sure, be an invaluable piece of apparatus. The other difficulties we have had in working it have been—

1. The difficulty of finding a place in a works perfectly free from vibration.
2. When the apparatus is fixed some distance from the furnace, it means a difficulty in reading the indications, as two persons are then required, one at the furnace and another to watch the galvanometer.

Perhaps you could kindly give us the benefit of your advice in this matter.

Reply from Professor H. le Chatelier.

Paris, 10 *février*, 1891.

Monsieur,

Ma communication à la Société d'Encouragement n'a pas été publiée mais j'ai communiqué mes résultats numériques à Mr. Howe, qui les a donnée dans l'*Engineering and Mining Journal* du 11 octobre, 1890, sous le titre "Pyrométrie data."

Je ne crois pas que mon pyromètre électrique puisse jamais être, suis d'une façon courante, entre les mains des ouvriers; l'électricité ne peut guères sortir du laboratoire. A mon avis les méthodes optiques seules pourrant fournir des appareils assez maniables pour les ouvriers. Je fais des récherches dans cette voie. . . .

Je pense le 23 et le 24 février venir à Londres pour le cinquantenaire de la Société Chimique de Londres. Avant de rentrer en France j'irons volontier jusqu'à Sheffield, que je ne connais pas encore. Pourriez-vous m'autoriser à visiter votre usine; je vous serons également très réconnaissant si, par vos relations, vous pouviez me procurer le moyen de visiter une verrerie et une fabrique de porcelaine.

Mais dîtes-moi franchement si ces demandes sont indiscrètes, et veuillez agréer l'expression de mes sentiments les plus dévoués.

H. le Chatelier.

Copy of Letter from Professor H. le Chatelier to Sir Robert Hadfield.

Paris, 10 *juin*, 1891.

Monsieur,

J ai terminé les récherches dont je vous ai parlé dans une lettre antérieure sur une pyromètre optique. Cette appareil permet à partir de 690° de suivre les variations de température à moins de 10° peu—c'est-à-dire que sa sensibilité est égale à celle de mon pyromètre électrique. Il m'a permis de mesurer les variations de température de l'acier coulant d'un four Siemens entre le commencenemt et la fin de l'opération. L'écart a été de 30° environ.

C'est un photomètre qui mesure l'intensité des radiations rouges émises par le corps chaud, en les comparant à celles d'une petite lampe à essence. L'appareil a la forme d'une lunette que l'on tient à la main.

Le seul inconvénient de cet appareil est d'exiger, si l'on tient à connaître les températures centigrades exacte, une graduation spéciale pour les différents corps chauds que l'on étude, parce qu'il n'ont pas exactement le même pouvoir émissif. On a pour chacun d'eux des courbes parallèles et peu distantes l'une de l'autre. Mais ceci a peu d'importance pour les usages industriels qui

n'exigent jamais la comparaison de températures des corps de nature très différente.

Cet appareil est construit par M. Peslin, successeur de Dubosq. J'en publierai une description à l'automne lorsque j'aurai terminé des mesures de pouvoirs émissifs que je poursuis en ce moment.

Veuillez agréer, Monsieur, l'expression de mes sentiments les plus dévoués.

H. LE CHATELIER.

PRODUCTION OF HIGH TEMPERATURE AND ITS MEASUREMENT.

Mr. E. F. Northrup (Princeton, N.J., U.S.A.) presented the following paper on "Production of High Temperature and its Measurement," which was communicated by the Secretary.

If the highly refractory properties of carbon are utilized, the attainment of high temperatures by electrical means, as in a Moissan furnace, is not difficult. The upper limit attainable is then determined by the vaporization-temperature of carbon. By employing carbon or graphite as a resistor we can readily obtain the highest temperatures in most gases and also in approximate vacuum. Furthermore, with suitable arrangements, a very high temperature which likewise is very uniform throughout a considerable volume (giving strictly black-body conditions) may be had, provided that carbon, in some one of its forms, is present.

The methods of obtaining high temperature with the use of carbon are not, however, more than a partial solution of the extremely important problem of the heat-treatment of materials at elevated temperatures. The reason lies in the fact that at temperatures which exceed the temperature obtainable with a platinum-wound furnace, carbon enters into chemical combination with a large number of the elements and reduces or otherwise changes many chemical compounds. Nor is it sufficient to keep the product to be treated from direct contact with the carbon. The reducing gas present is a carrier, at extremely high temperature, of exceedingly minute flying particles of what, I assume, is free carbon. Thus the glaze on a porcelain tube is quickly turned coal black when the tube is held in a carbonaceous atmosphere at, say, 1,300° C., and tungsten, molybdenum, and tantalum wires are quickly rendered brittle.

The attainment of high temperature, uniform throughout a volume, free from carbon may be obtained by using tungsten as a resistor, either in the form of a tube made to carry a heavy current, or in the form of wire or ribbon wound round a highly refractory tube. But here the tungsten must be protected from oxidation by filling the furnace with some reducing atmosphere, as hydrogen. A tungsten vacuum-furnace also is a possibility. The attainment not alone of high temperatures, but of temperature-uniformity with chemical purity at very high temperature, is the difficult but highly important problem for present-day solution.

Another consideration to be touched upon here is that of the inherent thermal inefficiency of every type of resistor-furnace when used for producing fusion of a product which melts at a high temperature. The character of the results obtained becomes at once apparent if we consider a special case. Assume we wish to melt with efficiency in a nichrome-wound furnace a given mass of copper. The copper would be contained

in a graphite crucible, which would be placed in a Norton alundum-tube wound on the outside with nichrome wire. Outside the wire-wound tube there would be a cylinder of the best obtainable heat-insulating material, with a radial thickness of several centimetres. With this arrangement the heat generated in the wire must travel to reach the copper through, say, 0·5 cm. of heat-insulating material, and to reach the outer wall of the furnace through, say, 10 cm. of heat-insulating material. Assume, when the current is first turned on, that the nichrome wire quickly attains its maximum safe temperature of, say, 1,282° C., and that at this first moment the copper and the outer wall of the furnace are both at 0° C. The temperature gradient from wire to copper and from wire to outer furnace wall will now be the same. But since the insulation-thickness which must be passed through for heat to reach the copper is but one-twentieth that which it must pass through to reach the outer furnace wall, heat will flow approximately twenty times as fast into the copper as it does toward the outer wall of the furnace. By this rapid inflow of heat into the copper the metal will soon be brought, though at a slower and slower rate, to its fusion temperature of 1,082° C. But at this stage the temperature gradient from wire to copper has become reduced to $1,282 - 1,082 = 200°$ C., while from the wire to the outer furnace wall the gradient remains, as at the beginning, 1,282° C. It follows that the ratio of the inflow to the outflow of heat is now greatly diminished, and that the heat which must be given to the copper to furnish its latent heat of fusion to melt it is but slowly supplied under a gradient of only 200°. Thus the heat available for fusion may become but a small fraction of the total heat generated in the furnace winding. The efficiency of the furnace as a *melting* furnace is, therefore, low, and if the furnace charge consists of a metal which fuses at just the maximum temperature to which the resistor may be brought, the efficiency of the furnace *for melting* becomes zero. A tubular resistor-type furnace will give in an empty chamber a high temperature very quickly, but it is, on the other hand, an inherently inefficient fusion-furnace, which becomes rapidly more inefficient as the temperature required for fusion approaches the safe operating temperature of the resistor-heater.

The above rather discouraging considerations led the writer to make two inquiries: first, what form should an ideal furnace take; and, second, is it physically possible to reach this ideal by any application of electricity?

The writer's conception of the ideal melting-furnace is one which consists of a crucible of cylindrical form (so proportioned that the ratio of its radiating surface to its volume is a minimum) that contains the product to be melted, either electrically conducting or insulating. This product by a process of *induction* alone should be capable of absorbing a large percentage of the power available, and thereby become quickly and uniformly heated until fusion with any desired superheat is obtained. The heat supplied in this ideal furnace should first and only make its appearance directly in the walls of the crucible, or, better, within the contents of the crucible. As power is continually supplied the temperature should rise and loss of heat by outward conduction and radiation should be negligible. The final possible temperature attainable should not be lower than a necessary limit set by the refractory properties of the crucible itself. A large percentage of the power supplied electrically and metered at its source should become directly transformed *within* the crucible into heat and not *pass* into the crucible from the outside by a process of heat-conduction.

If this ideal furnace is to be in part or wholly realized, it must be by some form of induction, obtained without the use of iron, for reasons which appear below.

The customary form of construction of the induction furnace does not permit the attainment of this ideal furnace in several particulars :

1. An electric circuit and an iron magnetic circuit are always interlinked. Thus, a circuit of metal is always interlinked with a complete or an approximate circuit of iron. This latter carries a primary winding, and the circuit of metal constitutes the secondary of a step-down transformer. This threading through the electric circuit of an iron magnetic circuit precludes the possibility of realizing the simple crucible form of construction above described.

2. The difference between the expansion with temperature of metals and refractories makes it practically impossible, without destroying the latter, to allow the ordinary induction furnace to cool down to where its charge solidifies. Refractory linings are invariably cracked when this is done. The furnace must be started with pre-melted material, and its charge must be removed before it is allowed to freeze.

3. The induction furnace constitutes a step-down transformer which necessarily has large magnetic leakage. The power factor may, therefore, be very low, the supply current lagging behind its e.m.f.

4. Very high temperatures cannot be obtained in the ordinary type of induction furnace because, if energy is supplied fast enough to replace the heat losses at high temperature, the molten material is ruptured by the mutual attraction of current elements. The limit is set for obtaining high temperatures by what Dr. Carl Hering has called the " pinch effect."

5. The ordinary induction furnace does not lend itself to such form of construction that the contents may be heated in controllable atmospheres or in vacuum.

With these limitations of the ordinary induction furnace in mind, the writer sought the underlying principle which would permit the attainment by electric induction of the ideal type of simple crucible furnace. This principle has been found, and a 20-kw. furnace embodying the principle has been made and very thoroughly studied. The furnace is a complete success. The principle upon which it operates will now be very briefly described.

Heating is obtained by inducing, with comparatively high frequency currents in an inductor coil which surrounds the crucible, very large currents in the walls of the crucible or in its contents, if these are electrically conducting. The induction is obtained by electromagnetic induction without the use of any iron. The furnace differs radically from all other types of induction furnace by the entire absence of any interlinkage of a magnetic with an electric circuit. The necessary high frequency of the inducing current may be obtained in more ways than one. The simplest and most obvious method is to employ oscillatory currents obtained from the discharge of condensers. These oscillatory currents pass through an inductor coil of about fifty turns which surrounds the crucible, and sufficiently separated from it to permit of both electrical and heat insulation. We thus have in effect a Tesla coil arrangement in which the voltage is transformed down and the current transformed up. It is to be noted that when a condenser of capacity C is charged to voltage V, energy is stored in the dielectric in potential form and in amount $\frac{1}{2}CV^2$. When the condenser is discharged this potential energy is released, and, becoming kinetic, may take the form of electric radiation as utilized

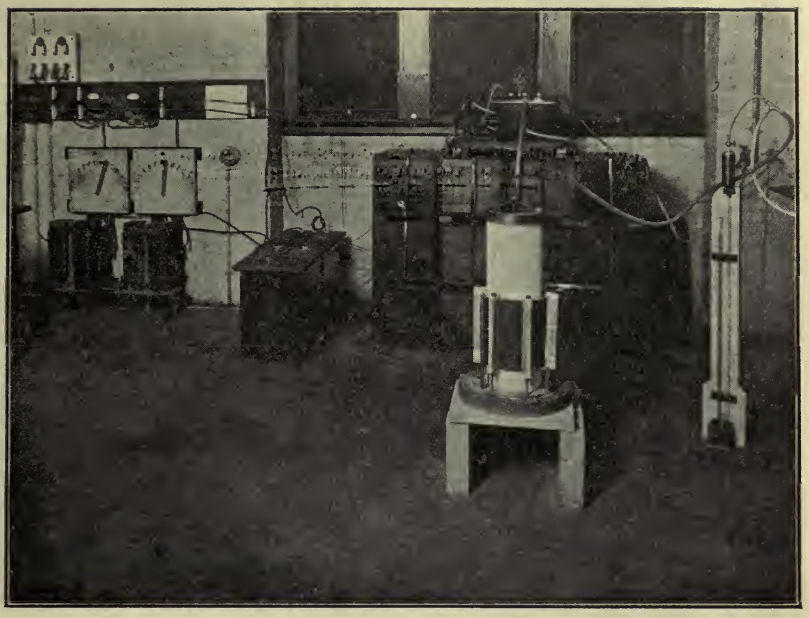

FIG. 1.—Northrup-Ajax High Frequency Induction Furnace.
General view of vacuum type.

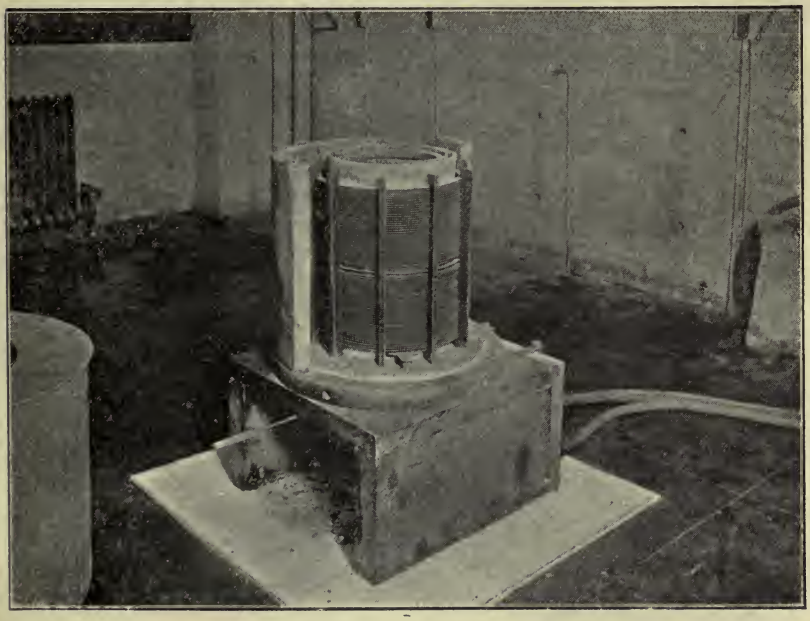

FIG. 2.—Northrup-Ajax Furnace—60-kilowatt type.
Furnace winding exposed to view.

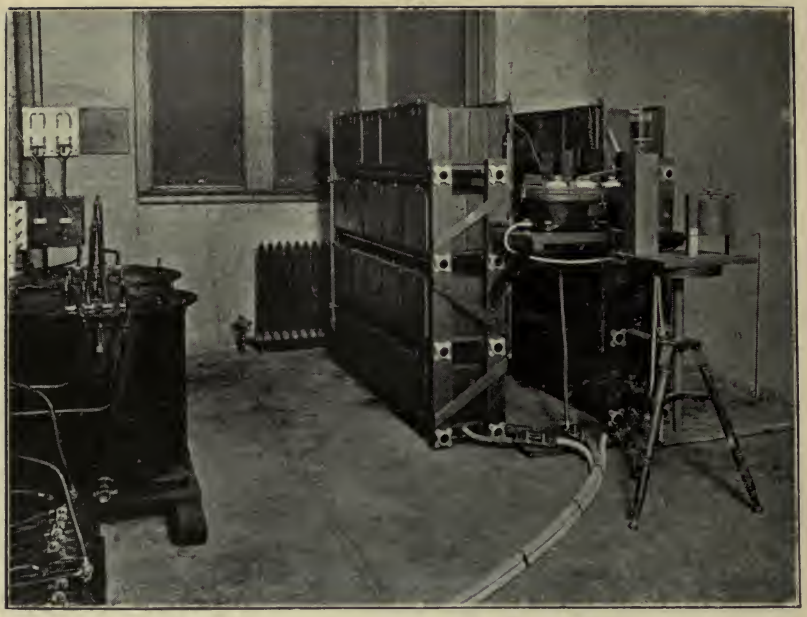

FIG. 3.—Oscillatory System for 60-kilowatt Furnace.
Condenser Tanks for A and B phases, 20 units on each phase.

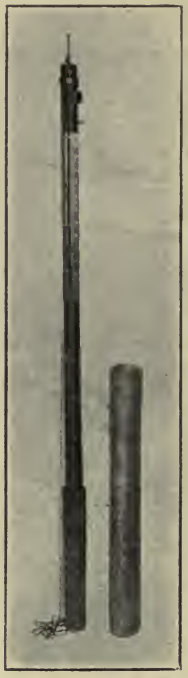

FIG. 5.—Tin Pyrometer and Outer Casing Tube.

in radio practice, or it may take the form of thermal energy or heat. When this principle is once recognized, it becomes purely a question of design and engineering practice so to construct apparatus and select conditions that very little energy is spent in radiation and a large percentage of energy is converted into heat within a crucible and its contents—the necessity of the interlinkage of an iron magnetic circuit with an electric circuit being entirely obviated.

Apparatus consisting of adjustable reactances, high-tension transformers, and an entirely new type of discharge gap (which is nearly silent and operates without moving parts), two banks of condensers and a furnace inductor winding, constitutes a complete outfit for operation on a two-phase, 60-cycle, 220-volt supply circuit.

Fig. 1 is a general view of an assembled 20-kw. furnace of the vacuum type.

Fig. 2 shows a metal-melting furnace (60 kw., since constructed) with its outer protecting case removed to reveal its construction.

The results so far obtained with this furnace (which is considered only as a model, since it is contemplated to construct this type of furnace in 50 or 60 kilowatt units) are about as follows:

1. It operates on a two-phase circuit, drawing an equal load from each phase.

2. It operates at full load with unity power factor for the supply circuit or with a slightly leading current.

3. It operates at any small fraction of full load without appreciable reduction in efficiency.

4. The metal-melting furnace will melt, starting at room temperature, about 45 lb. of brass in thirty-five minutes when watt-hour meters in the supply mains register a total power supplied of 18 kw.

5. The vacuum-type furnace, illustrated in Fig. 1, will bring a crucible of Acheson graphite 14 cm. in diameter and 18 cm. high, filled with tin or glass, to a temperature of well over 1,600° C. in forty to fifty minutes, and a vacuum of not less than 1 cm. of mercury can be maintained during the process. It should be stated, however, that certain kinds of glass evolve a vapour under reduced pressure which diminishes the vacuum and makes the glass frothy.

6. Cylinders or crucibles of the above dimensions, or smaller, made of graphite can be raised to a temperature of 1,600° C. with an almost perfect uniformity in their temperature distribution. Cylinders of other materials, as of iron, nickel, or nichrome, may be raised in temperature until they start to melt.

7. The thermal efficiency, defined as the ratio of heat energy developed within the crucible and its contents to kilowatt-hours supplied at switch terminals (both expressed in like units), may be made as high as 60 per cent. with the 20-kw. furnace illustrated, and it is thought that a greater thermal efficiency may be obtained in a furnace of larger power capacity.

The melting of platinum in vacuum has not yet been accomplished, but it is expected that this result will be attained when certain required devices have been constructed.

It is to be noted here that as progress in power and lighting distribution has come with increase in line voltage, so we may expect progress in electric heating by utilizing high voltages. The progress already attained has been reached by heating with induction at high voltage, and only a beginning has been made in a direction which gives rich promise of further development.

The furnace here illustrated has been operated at 5,400 and at 7,200 volts at the condenser terminals. The frequency is the natural period of the oscillatory circuit of either phase. About equally good results have been obtained when working with 25,400 cycles and with 12,500 cycles per second.

Protection from the high voltage is secured by surrounding the furnace casing with a grounded metal cage, and the crucible, in addition to being electrically insulated from the inductor coil with a cylinder of quartz glass, is likewise grounded.

The furnace above described and illustrated comes very near to a realization of the "ideal furnace" which we have pictured.

This furnace was developed by the writer for, and with the financial support of, the Ajax Metal Company, of Philadelphia, Pa. The development was made in, and with the facilities of, the Palmer Physical Laboratory of Princeton University.

The early construction of furnaces of larger kilowatt capacity is under contemplation, and a 50-kw. furnace is now nearly completed.* These furnaces should be particularly adapted to the melting of optical glass, high melting alloys, brass, gold, silver, etc.

It has been shown experimentally that by means of electromagnetic induction at high frequency, metal scrap, borings, turnings, etc., may be quickly raised to a melting temperature, then fused and superheated, even when contained in a refractory crucible of non-conducting material. Currents circulate in the subdivided mass, jumping with innumerable small arcs the contact resistances between particles. In this manner pure electrolytic iron, contained in a magnesia crucible, has been fused in vacuum, carbon and presumably every other source of contamination being entirely absent.

Finally, it is worthy of statement that we have in this method of heating a type of furnace which it is impossible to destroy by burning out, as the only parts which get at all hot are the crucible, its contents, and the immediate layers of refractory lining. A layer of heat insulation of "silox" about 1 cm. thick surrounds the crucible, and this has been found quite sufficient to maintain the inductor coil below a red heat when the crucible and its contents are above 1,400° C.

It is hoped that eventually, by using greater power input, it will be possible to melt metals in vacuum belonging to the tungsten group, and therefore make it possible to produce, free from carbon, any kind of very high melting alloy.

The Measurement of High Temperature.

We must here confine our remarks to the measurement of high temperature by means of direct insertion pyrometers, excluding from consideration the extensive subjects of radiation and optical pyrometry.

The limits to accuracy set for high-temperature direct-insertion pyrometers are determined chiefly by the inevitable chemical modification of the pyrometric substance rather than by its fusion or destruction. With the best types of pyrometer-casing tubes which are at present obtainable, at a temperature in the neighbourhood of 1,350° C. gases obtain access to the thermocouple wires, and contamination is produced by the chemical activity of the hot gases. If the pyrometer is inserted in a reducing atmosphere, this contamination is particularly marked.

* See p. 67.

Thus the writer has never been able to use successfully, except for very intermittent service, a platinum-rhodium thermocouple in a reducing atmosphere much above the melting-point of nickel. A thermocouple of tungsten-molybdenum, though giving but a feeble e.m.f., can be used to measure extreme temperatures if it can be protected from access of hot gases.

Up to about 1,300° C. the accurate measurement of temperature in any kind of atmosphere has been satisfactorily solved by properly constructed and protected platinum-rhodium thermocouples, the e.m.f. of which is determined by a potentiometer method. As a potentiometer is a somewhat delicate instrument to take into the factory, and as a direct deflection galvanometer, or milli-voltmeter, must be intrinsically sensitive to measure the feeble e.m.f. of a platinum-rhodium couple, the

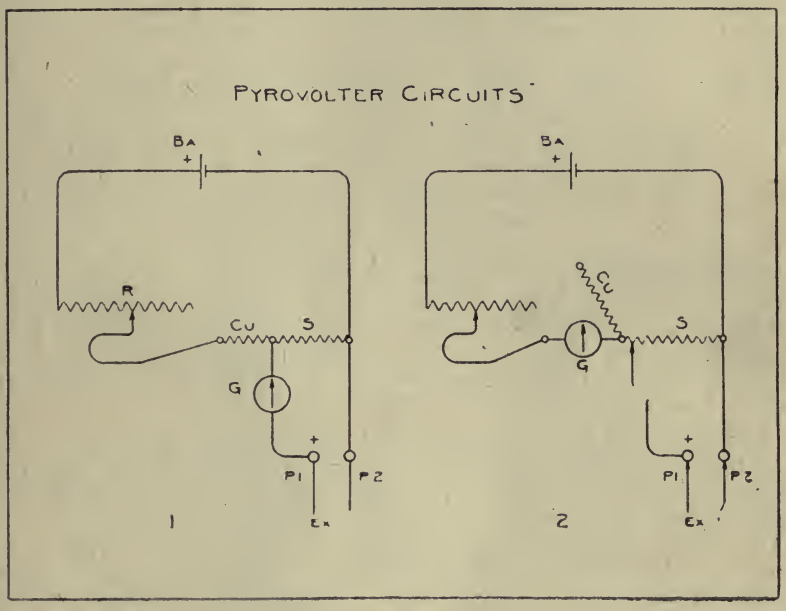

FIG. 4.

writer deemed it highly desirable to devise a robust portable instrument which would operate on the potentiometer principle, but give readings in milli-volts or degrees by the deflection of a pointer. The instrument devised for this purpose has the appearance and all the rugged characteristics of a voltmeter. It is marketed under the name "Northrup Pyrovolter."

The principle upon which the pyrovolter operates may be very briefly described as follows :

Referring to Diagram 1, Fig. 4, a small dry cell BA, contained in the case of the instrument, sends a current through the rheostat R and the fixed resistances CU (which is equal in value to the resistance of the copper coil of the moving element of the meter G), and S, a fixed resistance of manganin adjusted accurately with potential tap-offs. The value of the resistance included between these potential leads determines the range of the instrument. The current flowing through S is varied by the rheostat R, so that a varying e.m.f. is applied to these potential leads due to the drop of potential over the resistance S. The moving element

is connected in series with the unknown e.m.f., Ex (through the binding posts P1 and P2), across this varying potential, so that the meter serves as a galvanometer to establish a balance between the unknown Ex and the drop across S. This adjustment is effected by turning the large black button (marked " Off ") in the lower right corner of the instrument, in a clockwise direction, to increase the current flow through S, thus increasing the drop across S. When the balance has been attained, as is shown by the pointer of the instrument resting over the extreme left end of the scale (where a long, fine line is drawn to assist in setting the pointer accurately for this balance), the small button in the lower left corner of the instrument is pressed, which changes the connections to those of Diagram 2.

In the new connections (Diagram 2), it will be noted that the pressing of the button has substituted the meter G for the resistance Cu. This substitution is permissible for all temperatures, since both elements are copper and hence always of the same resistance ; so that now without affecting the conditions of the circuits, there has been introduced a meter which measures the current flowing through S, and since the drop across S is proportional to the current flowing through S, the scale of the meter is marked off to read the drop across S, and this drop having been just balanced against Ex, we have the instrument indicating the value of Ex.

In effect, the pyrovolter principle provides a means of operating a deflection instrument on the potentiometer principle, wherein the accuracy and permanence of the instrument basically depend upon a permanent magnet rather than upon a standard cell, in that the " current constant " of the instrument is all that affects the readings, the resistance S being once fixed. The practicability of the principle is at once evident, since the permanence of a permanent magnet is the basis of the calibration of the instrument.

Some of the advantages secured with this type of instrument for measuring millivolts by reading a deflection, and consequently the corresponding temperature indicated by either a base or noble metal thermocouple, may be enumerated as follows : Sufficient sensibility is secured in a rugged instrument so that temperatures indicated with platinum-rhodium couples may be read with satisfactory accuracy. As the instrument operates on a potentiometer principle, the resistance of the thermocouple itself and the thermocouple leads may vary within wide limits without affecting the accuracy of the readings. The instrument is not limited to a single range, but as many as four ranges may be conveniently embodied in one instrument. The indications of the pyrovolter are theoretically and practically independent of the temperature coefficient of the instrument itself.

Though thermocouple methods of reading temperatures meet most of the requirements of laboratory and factory up to the safe working temperature limit of the platinum-rhodium couple, there are many industrial operations, carried on at higher temperatures, where a direct-insertion pyrometer which measures these accurately would be very welcome.

Nature has provided us with a pyrometric substance which promises to give the result desired. This pyrometric substance is the metal tin. It possesses among the metals some unique characteristics. Tin melts at 232° C., and the writer knows from personal study that it does not evaporate appreciably nor boil at 1,680° C. According to a determination by Greenwood * its boiling-point is 2,270° C. Thus the range of tempera-

* *Chemical News*, 100, 1909.

ture in which tin is molten, about 2,000° C., is greater than that of any other known substance. Tin does not form a carbide in the presence of graphite, and maintains its purity in an atmosphere of CO at the highest temperature at which it is molten. To these properties are added others

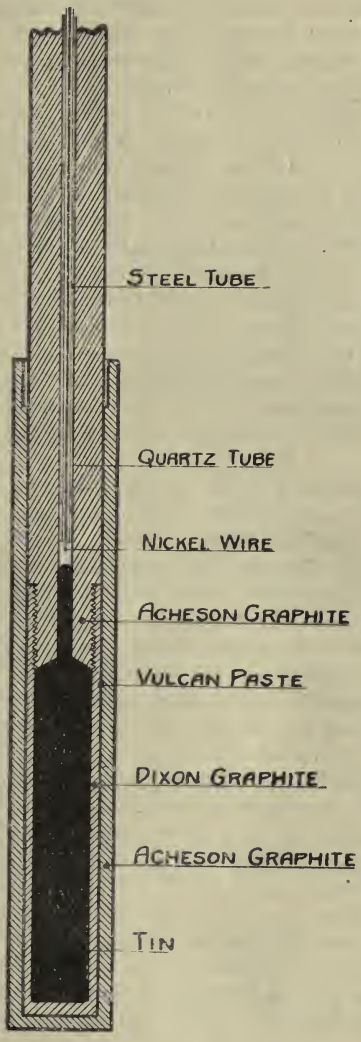

FIG. 6.—Cross-sectional View of Tin Pyrometer.

which particularly adapt it to pyrometric uses. Thus, it increases in resistivity when in the molten state, and also in volume in a strictly linear manner within increase of temperature. At least this is true up to the highest temperature at which accurate observations have been made, which is 1,680° C.

The writer has taken advantage of these characteristics of pure tin

for measuring temperatures above 1,600° C. and as low as the solidification-point of tin. He has used a method employing the increase in the resistivity of tin with temperature, and has developed in this connection an instrument called a "resistometer." * More recently he has developed a tin-pyrometer which depends for its indications upon the linear expansion of tin. The instrument is constructed on the general lines of a very large mercury thermometer. A first instrument which was recently constructed for industrial use to measure the temperature of a brick furnace is illustrated in Fig. 5. The pyrometer is shown in cross-section in Fig. 6.

The tin is contained in a "bulb" of close-grained graphite, and it expands, when the temperature exceeds about 700° C., into the graphite "stem." The height at which the column of tin stands is determined, in the present form of instrument, by electrical contact. The scale is laid off or calibrated by noting the height of the column of tin at some two temperatures chosen within the range of a platinum-rhodium couple. The scale is extended above the higher temperature upon the assumption that the expansion continues linear to the highest temperature for which the combination, graphite and tin, is suitable. The upper obtainable limit of temperature to which it is practical to go has not been actually determined, but it is known from personal observation that this limit is higher than 1,680° C., and it is thought to lie well above 1,800° C.

This pyrometer does not indicate, as a thermocouple does, a point-temperature, but registers the mean temperature over the space occupied by the pyrometer bulb.

There does not appear to be any serious difficulty in sight in preventing the graphite from oxidizing and slowly wasting away. To prevent this it is proposed to enclose the bulb and a portion of the stem in a tube closed at the bottom of a carborundum composition ("refrax," "silfrax," or "carbofrax," as made by the Carborundum Company of Niagara Falls). In the small clearance space between the bulb and the inside of this tube there may be inserted a filling of molten tin or a high melting glass. This jacket of molten tin or glass is expected to make a perfect shield against the attack of oxidizing gases upon the graphite of the bulb. Of course, this type of pyrometer is intended only for permanent installation in an industrial furnace of comparatively large dimensions, and the tin-pyrometer as now constructed must be maintained approximately in a vertical position.

It should be stated that while the writer has the highest confidence in the future practical application of this very high temperature direct-insertion pyrometer, it has not, at the present writing, been tried out in industrial situations, so that it may be pronounced a proved commercial success—but the principle is correct and further developments are quite sure to follow.

In closing, the writer would urge upon all investigators in the field of high temperature to consider the great possibilities of the metal tin for extending the fundamental temperature scale above 1,550° C., the present limit of the gas thermometer. Tin can be obtained as pure as nitrogen gas, and when in the molten state is quite as independent as a gas of its past physical history. Only chemical contamination and

* "New Method of Measuring Resistivity of Molten Materials: Results for Certain Alloys," by E. F. Northrup and R. G. Sherwood, *Journal of the Franklin Institute*, October, 1916.

temperature can affect either its resistance-change or its volume-expansion, and its chemical purity is easily controlled. Its resistance-increase and its expansion characteristics are, we firmly believe, as regular as is the increase in pressure of a gas of constant volume when its temperature is increased. Pure graphite, which makes an ideal container for tin, has an almost negligible expansion, and it is certain that both tin and graphite are undisturbed by a temperature elevation which goes far beyond that at which any gas can be used pyrometrically.

PALMER PHYSICAL LABORATORY,
PRINCETON, N.J., U.S.A.
September, 1917.

PYROMETER STANDARDIZATION.

A paper on " Pyrometer Standardization," by **Mr. Ezer Griffiths, D.Sc.**, and **Mr. F. H. Schofield, B.A., B.Sc.**, of the National Physical Laboratory, was read by Dr. Griffiths.

The increasing demands of the industries for temperature measuring and recording appliances have greatly stimulated progress in pyrometer construction, with the result that at the present day it is possible to measure temperatures over a very wide range—from that of liquid air to molten steel—with robust pyrometers of ample sensitivity. In fact, the sensitivity of some is so great that one is apt to exaggerate the accuracy of the measurements on account of the precision with which the scale of the instrument may be read.

The object of this paper is to indicate the basis of the temperature scale of the practical type of pyrometer, and also to set out some of the errors to which pyrometric observations are liable.

It is now generally agreed upon that the standard scale of temperature should be the thermodynamic. The advantage of this from the practical point of view is that it permits of the evaluation of high temperatures, on the basis of the radiation laws, on a scale consistent with that obtained by means of the gas thermometer at lower temperatures. The theoretical advantages of this scale need not be considered here.

Lord Kelvin showed that it was possible to realize this ideal scale of temperature through the intermediary of the gas thermometer. A " perfect gas " * would give a scale identical with the thermodynamic, while that obtained by the use of the more permanent gases—nitrogen, helium, and argon—requires a small correction to convert to the thermodynamic scale. It will be seen then that the ultimate scale of temperature is that of a gas thermometer suitably corrected.

In passing, it may be remarked that the corrections required to convert the scale of the constant volume nitrogen thermometer to the thermodynamic increase with temperature, amounting to about $+0{\cdot}7°$ at 1,000° C. They are, in fact, almost within the limits of the possible error of experiment in gas-thermometer observations.

Hence the problem of pyrometer standardization resolves itself to an empirical calibration of the pyrometer, whether mercurial, thermoelectrical, or radiation, by comparison with a gas thermometer.

Needless to say, that comparison cannot be a direct one for each instrument requiring a temperature scale, since the gas thermometer in its present form is one of the most fragile and cumbersome of physical

* *i.e.* one which obeys Boyle's law and one in which free expansion with no external work would cause no change in temperature.

instruments. Consequently, the scale of the gas thermometer is preserved by means of auxiliary standards—the mercurial thermometer, thermoelement, or resistance thermometer, or by a series of freezing-points or boiling-points of pure substances.

So the steps by which the scale of a pyrometer is obtained are generally as follows :—

(1) The gas-thermometer worker makes a comparison of his instrument with a thermoelement.

(2) This calibrated thermoelement is then employed to determine the freezing-points of a number of pure metals.

(3) The observer who wishes to calibrate a pyrometer standardizes a thermoelement by freezing-point determinations, assuming the values given by the gas-thermometer worker for these transition points.

(4) The pyrometer and thermoelement are then compared under suitable conditions.

Examples of this procedure are given later in the Paper.

THE GAS THERMOMETER AND THE INTERNATIONAL SCALE OF TEMPERATURE.

For nearly a hundred years researches on gas thermometry have been in progress almost without interruption, and the range $-200°$ to $+1{,}600°$ C. has been traversed.

The practical difficulties of gas-thermometer work at high temperatures are very considerable, particularly in connection with design of furnaces for obtaining uniformity of temperature over the space occupied by the bulb. Consequently the results obtained by different investigators often show divergencies of serious magnitude, resulting almost in every worker at high temperature having a scale of his own.

Before the war an effort was made to arrive at international agreement as to the adoption of a uniform temperature scale by the three national standardizing laboratories.* The experimental data given by various investigators with the gas thermometer were critically considered, from which the most probable values to be given to the " fixed points " were deduced. While substantial agreement was arrived at concerning the main points at issue, the outbreak of war prevented formal acceptance of a common scale of temperature.

The National Physical Laboratory decided to adopt for its own purposes, from the commencement of 1916, as its fundamental scale of temperature, the Centigrade thermodynamic scale. In order to realize this scale conveniently with the highest accuracy, and to promote the general use of the same temperature scale in both scientific and industrial circles, the following alternative methods have been adopted as a basis for attaining a practical or working scale of temperature :—

The Hydrogen Scale.

In the interval between ($0°$ C.) and ($100°$ C.) the practical scale is realized with the exactness required for work of the highest precision in the scale of the constant-volume hydrogen thermometer, having for fixed points the temperature of pure ice melting under normal atmospheric pressure ($0°$ C.), and that of the vapour of distilled water in ebullition under normal atmospheric pressure ($100°$ C.).

* National Physical Laboratory, National Bureau of Standards, Washington, Physikalisch-Technische Reichsanstalt.

The Platinum Resistance Thermometer.

In the interval between the freezing-point of mercury and the boiling-point of sulphur the practical scale is realized with sufficient exactness by the platinum-resistance thermometer standardized at the temperatures of melting ice (0° C.), of the vapour of water boiling under normal atmospheric pressure (100° C.), and of the vapour of sulphur boiling under atmospheric pressure in a specified form of apparatus and under specified conditions. The temperature of the vapour under these conditions is to be taken as 444·5° C. The temperature t on the international scale is deduced from the resistance of the platinum thermometer by the formula—

$$t-pt=\delta\left\{\left(\frac{t}{100}\right)^2-\frac{t}{100}\right\}$$

where $pt=100\times(R-R_0)/(R_{100}-R_0)$, and R, R_0, and R_{100} are the observed resistances of the thermometer at temperatures $t°$, 0°, and 100° respectively. The platinum of which the thermometer is made should be of such degree of purity that the value of δ in this equation should not be greater than 1·52 and R_{100}/R_0 should not be less than 1·386.

The boiling-point of sulphur, T_s, at pressure p millimetres is connected with that at standard pressure, 760 millimetres, by the formula—

$$T_s=444\cdot5+0\cdot0908(p-760)-0\cdot000047(p-760)^2.$$

The relation between the scale thus realized and the fundamental scale will be defined more closely as soon as a sufficient degree of concordance has been reached in the measurements. There is at present, however, every reason to believe that, over the interval 0° C. to 100° C., the scale thus defined is in agreement with the hydrogen scale of the International Bureau within the limits of experimental error required in most practical thermometric work.*

The Fixed-point Scale.

The practical scale is also realized with sufficient exactness by the use of the following fixed points, in addition to the three fundamental points above specified :—

		Temperature on the Thermodynamic Scale.
Boiling-point of oxygen	−182·95°	+0·01258(p−760) −0·0000079(p−760)²
Boiling-point of carbon dioxide ..	−78·5°	+0·01595(p−760) −0·0000111(p−760)²
Freezing-point of mercury		−38·88°
Transformation-point of sodium sulphate		32·38₄°
Boiling-point of naphthalene	217·96°	+0·058(p−760)
Boiling-point of benzophenone ..	305·9°	+0·063(p−760)
Melting or freezing-points of—		
Antimony		630°
Silver (in a reducing atmosphere)		961°
Gold		1,063°
Copper (in a reducing atmosphere)		1,083°

* See the hydrogen scale above.

Fixed points of the second order are provided by the melting or freezing-points of—

Tin	$231{\cdot}8_4°$
Cadmium	320·9°
Zinc	419·4°
Common salt	801°

It will be observed that the highest temperature defined is that of freezing copper, the uncertainty of which probably does not exceed 2°, and the lower temperatures are known with correspondingly greater certainty.

At temperatures exceeding 1,100° but few investigations have been made with the gas thermometer. Holborn and Valentiner in 1906 made gas-thermometer observations up to 1,680° C., employing a bulb of pure iridium of about 50 c.c. capacity. Day and Sosman in 1911 published an account of an investigation which had been in progress for seven years at the Carnegie Institute. They employed a rhodium alloy bulb, which, although less rigid than iridium at high temperatures, had the advantage of not contaminating the thermoelements in the furnace.

The value 1,549° C. was obtained by Day and Sosman for the melting-point of palladium, for which Holborn and Valentiner gave the value 1.575°.

Temperature measurements above 1,000° with a platinum alloy thermoelement in the presence of iridium are rendered untrustworthy on account of the great contamination caused by the volatile iridium. Moreover, it is necessary to employ a thermoelement to transfer the scale, since the practical difficulties of determining freezing-points at high temperatures directly by means of the gas thermometer appear to be insuperable.

Day and Sosman for some time employed a bulb of platinum 10 per cent. iridium, but finally abandoned this for the 20 per cent. rhodium alloy.

The following values for "fixed points" above 1,100° were determined by Day and Sosman: nickel, 1,452°; palladium, 1,549°; and platinum, 1,755°, by extrapolation of the thermoelectric formula of their platinum–platinum-rhodium couples.

In passing, it may be remarked that numerous determinations of the same fixed points had been made previously by other observers employing thermoelements calibrated on the gas scale to 1,000° C.

Further research has shown that the temperature e.m.f. relationships for thermoelements will not bear extrapolation over long intervals, and consequently such determinations are now obsolete. It is now generally agreed that the function of the thermoelement is that of a convenient working standard for transferring the scale, and that it must be calibrated over the entire range on which it is to be employed.

The values given by Day and Sosman for the "fixed points" have been tacitly accepted by workers at high temperatures in recent years as a basis of a common scale of temperature. And beyond 1,550° C., the upper limit of gas thermometry, it is more rational to extend the scale on the basis of the radiation laws in view of their plausible theoretical foundation.

THERMOELECTRIC PYROMETERS.

The working standards are calibrated by determination of their e.m.f.'s at a number of well-established temperatures—the boiling-points of water, naphthalene, diphenylamine and sulphur, and the freezing-points of tin, zinc, antimony, silver, gold, copper, nickel, and palladium.

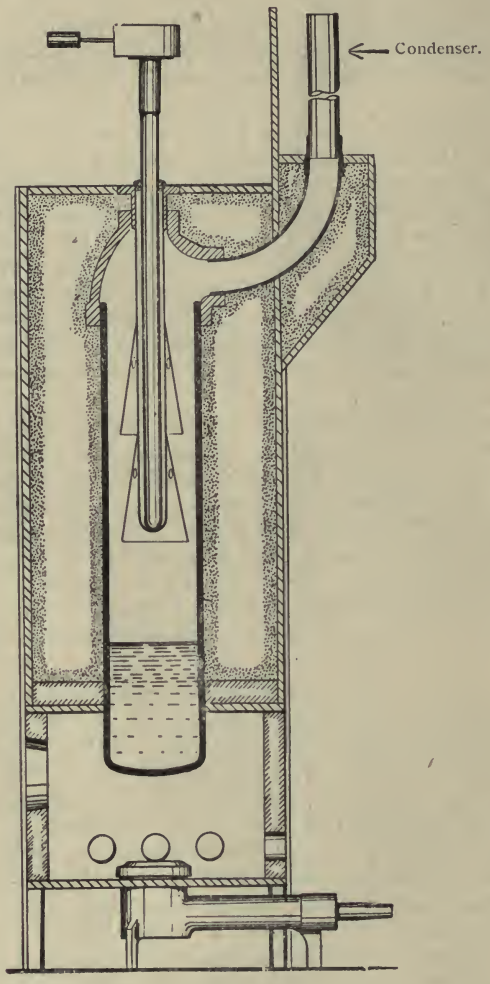

FIG. 1.

The boiling-points are determined in the usual Meyer tube form of apparatus introduced by Callendar and Griffiths for the standardization of resistance thermometers at the sulphur boiling-point or the N.P.L. modification shown in Fig. 1.

In the case of the metals, other than gold and palladium, cooling curves are taken with the sheathed couple immersed in the molten metal. The cold junction is maintained at 0° by immersion in ice, while the

e.m.f. is measured by a thermoelectric type of potentiometer. The crucible containing the metal is heated in a blast muffle and precautions taken against oxidation, etc. Ample depth of immersion should be given, and melting-points and freezing-points should agree closely.

The determinations of the freezing-point of nickel present exceptional difficulties. It requires a powerful blowpipe and refractory furnace linings. We have tried for linings, fire-clay, crude zirconia mixtures, and carborundum fire-sand admixed with a little borax. The last mentioned has proved to be the most satisfactory, and the lining, if worn, can be patched up without difficulty.

The metal must be melted in a neutral atmosphere, since the presence of oxide lowers the freezing-point about 10°, due to its absorption to form a eutectic.

It was found that a thin layer of fused borax efficiently protected the surface of the nickel. The borax, however, had a serious fluxing action on the crucible material, pitting it deeply, so that the life of the crucible was limited to a few melts.

Considerations of expense preclude the possibility of taking cooling curves for gold and palladium, and the wire method is convenient for these metals. In this the arms of the couple are joined up with a short loop of the metal. The thermoelement is then heated in a carbon spiral furnace with a liner tube of glazed porcelain, and its e.m.f. determined at the time of the breaking of the circuit.

A difficulty which sometimes occurs is the drawing together of the ends of the couple by the melting of the palladium. This trouble was eliminated by fixing a small rider of fire-clay to keep the wires apart. Leakage from the heating circuit occasionally caused discrepancies.

As an illustration of the concordance obtained in successive experiments the following values may be quoted :—

Experiment.	E.M.F.
1	18,382
2	18,374
3	18,372
4	18,300
5	18,336

Omitting experiment 4, the range of divergence is equivalent to 3° C.

A Suggested Fixed Point for Calibrating Thermocouples.

We may perhaps refer here to some recent work which we have been doing with a view to establishing a new " fixed point " at high temperatures. The scale above 1,000° C. at present depends on the freezing-points of gold (1,063°), copper (1,083°), nickel (1,452°), and palladium (1,549°), and in the long interval of 270° between the copper and nickel points only the melting-points of lithium meta-silicate (1,201°) and diopside (1,390°) have been established. Melting-point determinations are never quite so satisfactory as those of freezing-points, and the two substances named are not easy to prepare.

Our efforts were therefore directed to finding some freezing-point which would be easily reproducible and would help to bridge the gap between the copper and nickel points, and which could be obtained with the type of apparatus employed for the freezing-points of the metals. We find that a mixture of nickel and graphite exhibits a well-defined

eutectic with a freezing-point about midway between the two points. A specimen of the cooling curve for the eutectic, obtained in the usual way by immersing a sheathed thermo-junction in the mixture, is shown in Fig. 2.

Our work has not yet been concluded, but a provisional value of 1,330° C. may be given for the freezing-point. It is easy to reproduce, the main precaution necessary being to employ excess of graphite.

Temperature—E.M.F. Relationship.

Various empirical formulæ have been proposed for expressing the relationship between the e.m.f. and temperature of a platinum alloy thermocouple. No single expression of workable size holds over the

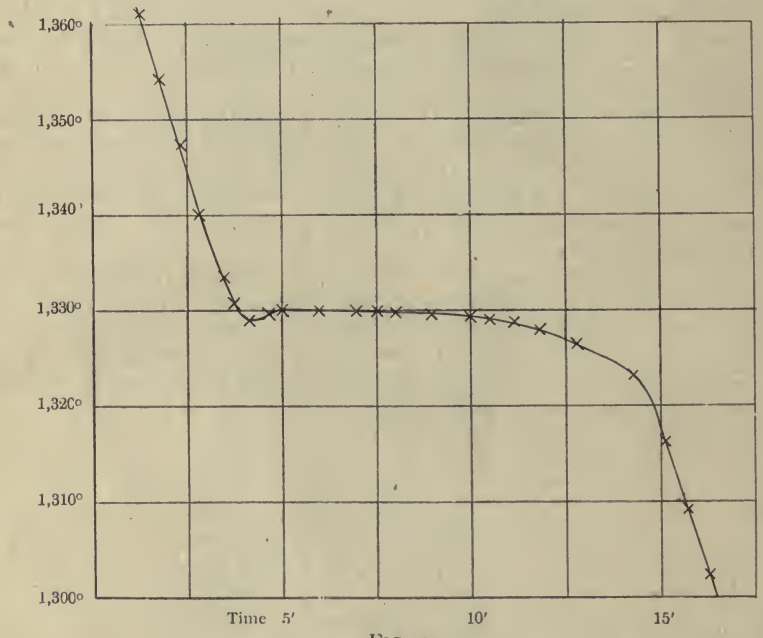

Fig. 2.

complete range 0° to 1,600° C. We find that the simplest procedure is to compute a table which represents a smooth curve through the experimental points. The values of the e.m.f. for every 10° C. are then set out in tabular form. From 200° to 1,000° C. a cubic curve represents the results quite closely, while above that temperature a parabola fits the observations.

Calibration by Comparison with a Standard Thermoelement.

The method of standardizing by freezing-point determinations should only be resorted to in the case of primary working standards. The calibration of one couple by direct comparison with another is both simple and expeditious.

Our general procedure is as follows: The heavy porcelain sheath is removed and the thermocouple wires are insulated by capillary fire-clay tubing or quartz. The junctions of the two couples are tied together

by a piece of pure platinum wire and inserted at the mid-point of an electric furnace. The couples are carried in a liner tube supported from the cold ends of the furnace to avoid leakage from the heating circuit into that of the potentiometer.

The e.m.f.'s of the couples are determined at a series of steady temperatures over the range.

Sources of Error in Thermoelectric Pyrometry.

(*a*) *Contamination.*

The inherent defect of platinum alloy thermocouples is their liability to become contaminated. It is essential to protect a thermoelement most rigorously from metallic vapours, reducing gases, and carbonaceous matter at high temperatures. Carbon alone does not appear to con-

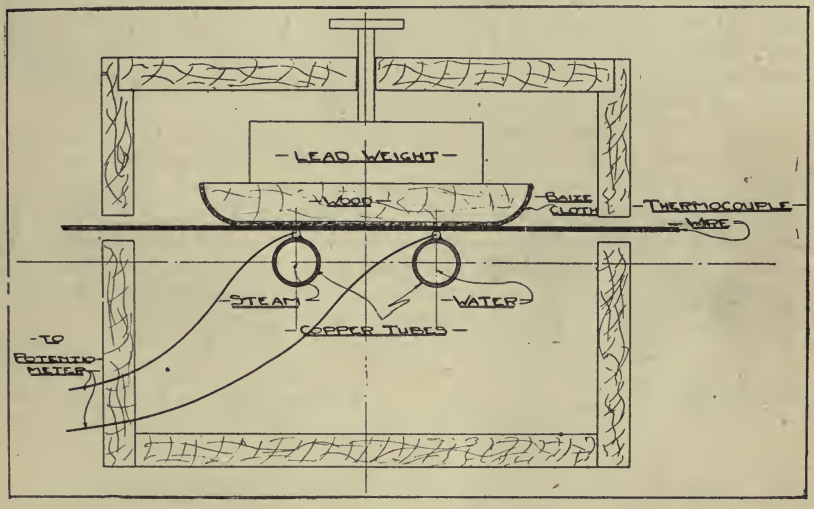

Fig. 3.

taminate : it is its presence as a reducing agent with other materials which yield contaminating products on reduction which must be avoided. In commercial outfits it is possible to secure ample protection by the use of glazed porcelain or a quartz sheath, with, of course, the introduction of a considerable time lag in the observations.

A form of contamination which it is impossible to eliminate completely is the volatilization of rhodium or iridium from the alloy limb on to the pure platinum limb. The effect is not nearly so pronounced with the rhodium as with the iridium alloys.

It is to be remembered that recalibration of a suspected thermocouple does not suffice to ascertain whether the " furnace end " is contaminated or not. Should the affected portion be within the uniformly heated region, it is immaterial what the wire is.

Apparatus for Detecting Contamination of Thermocouples.—Among the various methods of detecting contamination of thermocouples, that adopted by White, of the Geophysical Laboratory in America, is perhaps the most convenient.

In his arrangement two parallel wires of the same material (say, copper) are fixed at a certain distance apart and are maintained at different temperatures. The wire to be tested (say, platinum) is laid across the copper wires at right angles and pressed into contact with them by a weighted pad. By connecting the copper wires to a potentiometer the resulting thermal e.m.f. can be measured. The platinum wire is then moved until another section is in contact with the copper wires and the e.m.f. again measured. If the platinum wire were perfectly homogeneous, the value would be the same as before. By making successive small movements of the platinum wire it can be completely explored for homogeneity and any changes due to contamination detected.

A simple modification of the apparatus which we have found to give good results is illustrated in Fig. 3. The two copper wires are soldered on the top of two copper tubes which pass through the sides of a small wooden box. A stream of steam is circulated through one of the copper tubes and tap-water through the other. Two small holes in the other sides of the box serve to admit the platinum wire at right angles to the copper wires, and a hole in the top of the box suffices for raising and lowering the weighted pad. The use of a closed box protects the working parts of the apparatus from draughts.

Examples of some results obtained with this apparatus on platinum and platinum alloy wires are given below. The copper wires were 1 in. apart. The first reading in each series was taken at the " furnace end " of the wire under test, the second reading after moving the wire 1 in. across the copper wires, and so on. In the case of badly contaminated wires, where the values showed fluctuations of several per cent., a number of readings were taken for each inch and the averages entered below. The values refer to e.m.f.'s measured in microvolts.

Distances in Inches.	*A*.	*B*.	C_1.	C_2.	D_1.	D_2.
1	576	616	525	77	549	−418
2	573	623	520	72	544	−417
3	578	625	542	66	548	−436
4	578	629	554	63	537	−427
5	578	628	564	67	569	−440
6	575	627	567	77	588	−447
7	575	626	572	80	585	−453
8	574	628	578	80	590	−453
9	578	632	576	79	590	−453
10	578	636	582	79	587	−446
11	577	638	574	80	584	−448
12	577	639	576	80	586	−452
13	574	640				
14	576	641				
15	578	639				

A is a new platinum wire.

B is a platinum wire which had been used for ten or twelve hours in measuring temperatures up to 1,550°. The couple was protected by a sheath from a reducing atmosphere. The contamination is considerable for 2 or 3 in., and does not wholly disappear for 11 in. To get some idea of the actual errors in readings at high temperature in the case of this couple, the following observations were taken of the freezing-

point of silver. When the arms of the couple were twisted together and doubled back at a point 12 in. from the original junction, so that the contaminated part of the couple was put out of action, the correct value of 961° C. was obtained; with the first 8 in. of the couple out of action the value was 958°, while for the full length of the couple the value was only 946°—an error of 15°. The depth of immersion in the silver was about 1½ in.

C_1 and C_2 are the arms of a couple, platinum and 10 per cent. rhodium-platinum respectively, which have been contaminated by nickel owing to the sheath cracking. The contamination apparently extends for some 6 in. and has the effect of lowering the e.m.f. of both arms of the couple.

D_1 and D_2 are the platinum and platinum-iridium arms of a thermocouple which has become brittle near the junction from long usage. In this case the couple appears to be contaminated for 5 or 6 in.; the platinum arm shows a fall in e.m.f., while the platinum-iridium arm, which is negative relatively to copper, shows an increase in e.m.f. The two arms are thus tending to approach in value. This is probably an example of cross-contamination due to iridium having distilled from one arm and been partly deposited on the other.

(*b*) *Lag.*

The necessity of protecting the element from furnace gases, etc., by the use of a porcelain tube introduces another source of error when determining varying temperatures, namely, thermometric lag. This time lag can only be reduced by sacrifice of robustness of construction.

With base-metal pyrometers at temperatures up to 800° C. it is possible to work with the exposed elements or with the wires simply coated with a thin layer of asbestos-cement mixture, and so reduce lag to a minimum. Time lag is apt to be very troublesome when determining casting temperatures of molten metals.

(*c*) *Oxidation.*

The defect of base-metal thermocouples is the gradual oxidation of the metal, which, of course, increases the resistance. It is the common practice to employ a low-resistance indicator with this type of pyrometer, so as to obtain robustness. Hence change in the resistance of the wires by oxidation of the couple affects the total resistance of the circuit. We have noted errors of as much as 50° C. at 600° C. due to this cause, although the e.m.f. of the couple was unaltered when measured on a potentiometer.

RESISTANCE PYROMETERS.

Siemens' resistance pyrometer was the first application of electrical methods to the measurement of furnace temperatures. This instrument fell into disrepute because at that time (1871) the precautions necessary to protect the platinum from contamination were not clearly understood. The anomalous results which were observed with the early pyrometers were due to the effect of reducing gases on the silica of the fire-clay bobbin liberating traces of silicon, which combined with the platinum.

The rapid development of the thermoelectric method and the simplicity of the appliances necessary diverted attention away from the resistance

pyrometer, and consequently its development for industrial work has been slow.

In view of the shortage of platinum and the metals of the same group, it might be well to reconsider the position.

The quantity of platinum required for the "bulb" of a resistance pyrometer is trifling, and if some satisfactory substitutes could be devised for the customary platinum leads, the biggest item in the cost of the pyrometer would be eliminated.

The work of Callendar and Griffiths has proved conclusively that the resistance thermometer standardized in ice, steam, and sulphur vapour will give a scale identical with that of the gas thermometer. Consequently, calibration at three temperatures suffices to fix the scale for the range −40° to 1,000° C. The apparatus employed for the ice and steam-point is familiar to all. For the sulphur-point the apparatus illustrated in Fig. 1 is employed. It differs from the usual type chiefly in the fact that it is made of metal instead of glass, and that the thermometer to be tested, instead of being immersed directly in the vapour, is placed in a re-entrant metal tube permanently fixed in the centre of the main vessel.

The asbestos cone commonly surrounding the bulb of the thermometer is replaced by two metal cones fastened directly to the exterior of the re-entrant tube. The vessel is made from a discarded gas cylinder and steam-pipe fittings. The condenser is a quartz tube, which is less liable to crack the glass, the translucent variety of which is quite satisfactory. The level of the vapour when the apparatus is working normally should be at a height of about 6 in. up the condenser.

From the observations the value of δ in the formula

$$t-pt=\delta\left\{\left(\frac{t}{100}\right)^2-\left(\frac{t}{100}\right)\right\}$$

is calculated. The resistance bridge or indicator is calibrated independently.

The resistance thermometer, if handled with care, is remarkably free from liability to give false readings, and in case of doubt all that is necessary is to check the resistance at the ice-point. Probably its greatest defect is the time lag when measuring moving temperatures.

TOTAL-RADIATION PYROMETERS.

Theoretically, an instrument whose indications measure a property of radiation should only require a comparison at one temperature to interconnect its scale with that of the gas thermometer. But this procedure would imply two conditions. First, that the laws of radiation have an indisputable theoretical foundation, and second, that it is possible so to design an instrument that its scale can be calculated with mathematical certainty from the radiation law. In practice neither of these conditions can be complied with.

The Stefan-Boltzmann law is perhaps the best established, both theoretically and practically, of all laws of "radiation." The experiments of Lummer and Pringsheim over the range of 100° to 1,000°, and the later observations of Mendenhall and Forsythe at 1,100° and 1,550° C.,

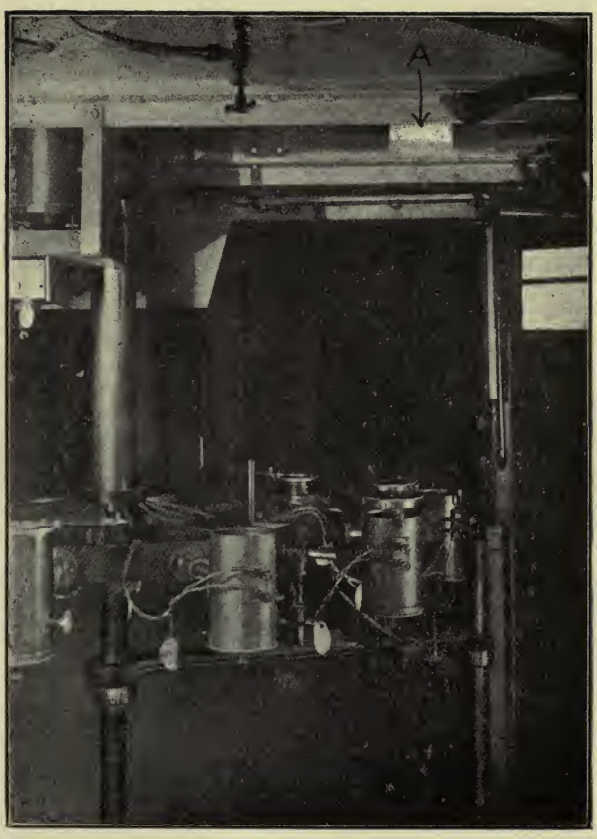

FIG. 4.—The extension on the mouth of one of the furnaces will be seen at A.

have proved conclusively that the law is valid over the entire temperature range covered by the gas thermometer. It may therefore be employed with confidence as the basis of methods for the evaluation of high temperatures.

In radiation pyrometry the " black body " occupies much the same rôle as the " perfect gas " in gas thermometry—an ideal which can be closely approximated to in practice, but never fully realized.

The thermoelectric type of radiation pyrometer is sufficiently well known to need no description. Its standardization is effected by a comparison with a thermoelement over the range 500° to 1,400° C., while extrapolation beyond this temperature can be effected on the basis of the formula $e=aT^b$, where e is the e.m.f. and b is constant, nearly 4. Several factors contribute to cause variations in the value of this index from 4.

The e.m.f. generated by the thermocouple in the instrument is not a linear function of the temperature rise. The rate of heat loss from the junction is not strictly proportional to its temperature excess. Stray reflections from the walls may reach the receiving disc. Consequently the index b has to be determined for each individual instrument.

Calibration.

For the calibration of instruments which are to be employed as working standards, electric furnaces are employed.

The apparatus in use at the National Physical Laboratory has been developed by Dr. Harker and Mr. Blackie, and is shown in Fig. 4. A series of four large furnaces are mounted on an iron platform mouth downwards. Each is provided with suitably disposed diaphragms, and the pyrometers are focused on a plug of refractory material fixed in the centre of the furnace. Across the face of each plug a platinum–platinum-rhodium thermoelement is stretched, so that the mean temperature is obtained with accuracy.

Sources of Error.

While it is possible in the laboratory to reproduce " black body " conditions with considerable accuracy, in the industries it is often impossible to approximate more than roughly to such conditions.

The radiation from muffles and furnaces is generally sufficiently near to full radiation to make the application of any corrections to the pyrometer readings unnecessary, but the radiation from metallic objects departs considerably from the ideal contemplated by the Stefan-Boltzmann law. When the surface is oxidized the difference between the apparent and real temperature will be a function of the condition of the surface, and it is difficult to apply a correction with any degree of certainty. For example, Burgess found the apparent freezing-point of copper with a clear surface to be 600° C., compared with the true value 1,083° C., while the surface covered with cuprous oxide gave a temperature 300° higher than the clean surface.

The total-radiation pyrometer is of very limited use with molten metals, since such surfaces can never be freed from haze or fog, and the radiation from the walls of the furnace or crucible reflected at the molten surface is apt to introduce serious errors. It has, however, the advantage over the optical pyrometer insomuch that it can be made recording.

OPTICAL PYROMETERS.

Of the laws of radiation, those for the representation of the distribution of energy in the spectrum are the least satisfactory theoretically, whilst yet of the greatest utility practically. Wien's law—

$$E_\lambda = \frac{C_1}{\lambda^5 e^{C_2/\lambda T}}$$

is based on plausible assumptions concerning the mechanics of the radiation emission from atoms. It represents with fair accuracy the distribution of energy in the spectrum, but fails for large values of λ or of T, i.e. if the product λT exceeds 3,000. Planck's formula—

$$E_\lambda = \frac{C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)}$$

is capable of representing the experimental facts over the entire range, but is scarcely more than an empirical formula. Its deduction from theoretical considerations requires assumptions which are irreconcilable with the fundamental principles of electrodynamics.

It will be observed that Planck's equation reduces to that of Wien's for small values of λT. Hence, in practical pyrometry Wien's form is generally employed, on account of its convenience in its logarithmic form—

$$\log E = \log (C_1/\lambda^5) - \frac{C_2}{\lambda T},$$

i.e. a linear relation between log E and $\frac{1}{T}$.

Practical Types.

The three commonly used types of optical pyrometers are (1) the disappearing filament type; (2) the polarizing type; (3) the wedge absorption type.

From the point of view of sound theoretical foundation for the design of the instrument, the polarizing type is the best, since essentially it is a photometer—in fact, an adaptation of the König spectrophotometer. Consequently the temperature scale can be readily extrapolated to high temperatures on the basis of Wien's or any other radiation law. Further, the scale is independent of the permanency of the electric lamp which is set from time to time against an amyl-acetate lamp.

The disappearing-filament pyrometer is a modified telescope, in which the image of the hot object is focused in a plane containing the filament of an electric lamp. So it is easy to pick out the object whose temperature is desired, and readings may be obtained to the limits of visibility.

Calibration.

The calibration of optical pyrometers is effected in a manner similar to that described for total-radiation pyrometers, namely, by sighting them on a " black body " furnace the temperature of which is determined by a thermocouple.

This procedure has the advantage of not presupposing perfection of the optical system or a knowledge of the wave-length of the red light transmitted by the filter glass.

The calibration of the polarizing type is based on the following theoretical considerations :—If I_1 and I_2 are the intensities of two plane polarized beams of radiation matching at angles ϕ_1 and ϕ_2 a beam of constant intensity, such as that from an electric lamp, when viewed through a nicol prism, then—

$$\frac{I_1}{I_2}=\frac{\tan^2\phi_1}{\tan^2\phi_2}.$$

In optical pyrometry, by the insertion of a suitable red glass in the path of the two beams, it is possible to work with narrow spectral bands* and consequently apply Wien's law, according to which the intensity of light of wave-length emitted by a " full radiator " is given by the expression

$$I=\frac{C_1}{\lambda^5}e^{-C_2/\lambda T}.$$

If

I_1 is intensity at temperature T_1,
I_2 " " T_2,

so that

$$\frac{I_1}{I_2}=e^{C_2/\lambda(1/T_2-1/T_1)}.$$

Hence—

$$\frac{I_1}{I_2}=\frac{\tan^2\phi_1}{\tan^2\phi_2}=e^{C_2/\lambda(1/T_2-1/T_1)}.$$

Taking logarithms—

$$2(\log\tan\phi_1-\log\tan\phi_2)=\frac{C_2}{\lambda}\left(\frac{1}{T_2}-\frac{1}{T_1}\right),$$

so that the relation between ϕ and T is of the form

$$\log\tan\phi=a+\frac{b}{T}.$$

Hence, theoretically, by plotting log tan ϕ against $\frac{1}{T}$ a straight line should be obtained.

In Fig. 5 the calibration points for an instrument are shown graphically, and it will be observed that Wien's law is obeyed quite satisfactorily.

By the insertion of a neutral-tinted glass in the path of the radiation a second scale covering a higher range of temperature may be obtained. The two lines should, of course, be parallel (see Fig. 5). The second scale can consequently be extended beyond the limits of the scale covered by gas-thermometer work with a considerable degree of confidence.

The form of the temperature-angle relationship is shown in Fig. 6.

It is interesting to note that, according to theory, the value of b in the equation above-mentioned should be the constant for all instruments using light of the same wave-length. We find considerable departures in the case of the individual instruments, but taking the average of 100 scales which have been recently calibrated, the value of b was found to be 4,860. The theoretical value would be 4,840 for a wave-length of 0·65 μ, commonly used in these instruments.

* A good red glass will give a band extending from the orange red (0·62 μ) to the limits of visibility towards the infra red and with a maximum transmission at 0·65 μ.

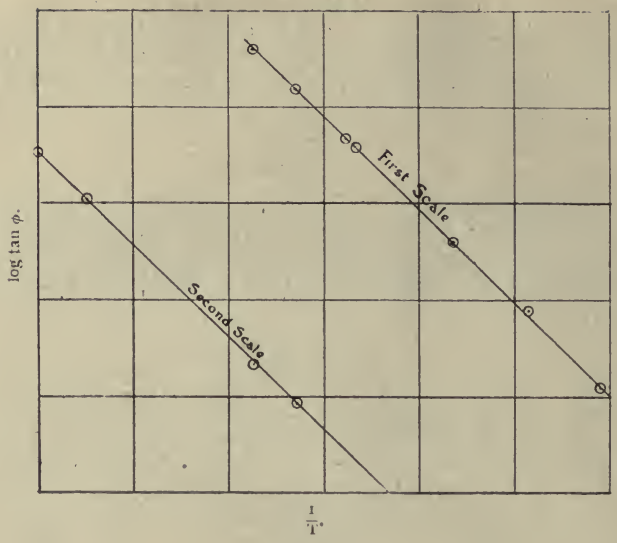

FIG. 5.

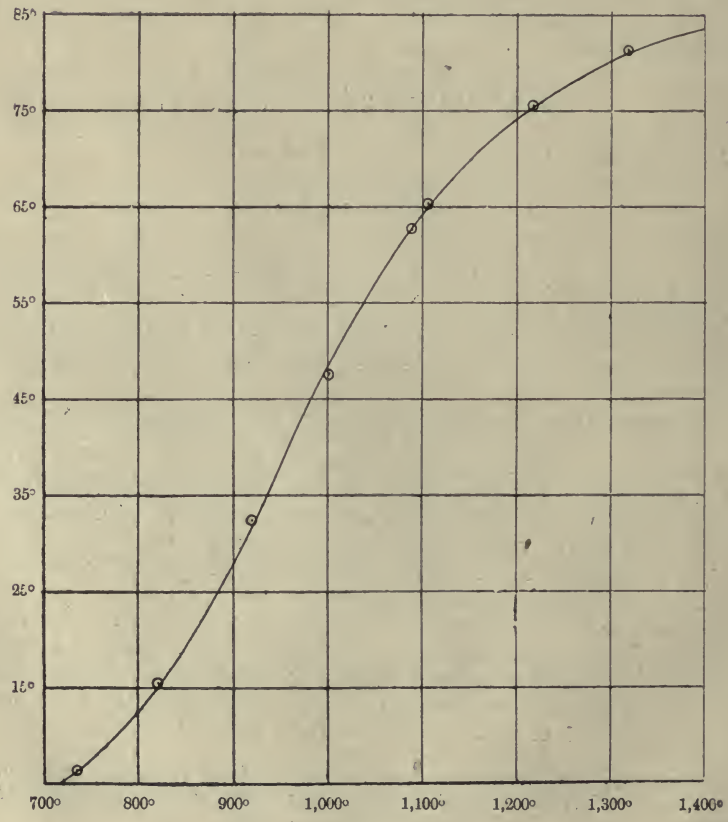

FIG. 6.—Temperature ° C.

In the case of instruments to be employed as working standards, it is advisable to check the calibration by direct observations of the melting-points of pure metals. A wire of the metal is stretched across the face of a diaphragm in the furnace and the temperature gradually raised. The melting of the metal is indicated by the breaking of the electrical circuit, and the temperature at this instant is noted.

We have found that the gold and palladium points are very satisfactory for this purpose. Copper requires a reducing atmosphere, and consequently it is necessary to close the front of the furnace with a glass window and make corrections for the absorption of the glass.

For routine work in calibrating optical pyrometers, platinum-wound furnaces with thermocouples may conveniently be used to a temperature of 1,350° C. Above this it becomes necessary to rely on a comparison with a standard optical pyrometer which has itself been calibrated, in terms of the fixed points, to the highest possible limits. Provided that the standard instrument and the one under test are of the same type and use the same wave-length, there is little or no advantage to be gained by having a "black body" as a source of comparison—any hot object of suitable size and sufficiently uniform and constant in temperature will serve as well.

Our experience is that the tungsten arc-lamp described by Gimingham and Mullard and manufactured by the Edison and Swan Electric Company is very satisfactory for the purpose. The lamp consists essentially of a small plate and sphere of fused tungsten, between which the arc plays, together with an auxiliary gear for striking up the arc, the whole being enclosed in a glass bulb in an atmosphere of nitrogen. Viewed from the side opposite to that on which the arc is striking, the plate presents a surface of uniform temperature which is sufficiently large to fill the field of a pyrometer of the polarizing type. The temperature remains constant so long as the energy is not varied, and by running the lamp off a battery and adjusting the energy to particular values, temperatures may be reproduced with very fair accuracy. The range is also very considerable. For example, one lamp which has been in use for over a year may be run from ·8 to 4·2 amperes, giving temperatures from 1,500° to 2,400° C. By the use of absorption glasses, the apparent temperature of this lamp may be cut down below 1,350° C., though it is not advisable to continue this process far, unless the absorption glasses are of exceptional quality, as colour-matching difficulties are likely to supervene.

The special advantage in using a tungsten-arc lamp as compared with a "black-body" source, such as a carbon-tube furnace, consists in the ease and certainty of manipulation and the enormous economy of time.

Sources of Error.

Errors due to departure from "black body" conditions are not so serious with optical pyrometers as with the total-radiation type. For instance, the corrections required to convert "apparent temperatures" of an oxidized iron surface to "true temperatures" only amount to 4° C. at 1,000° C. and are negligible up to 700°.

If the filter glasses are not fairly monochromatic, the personal equation of the observer comes in largely, especially at high temperatures, when differences of tint become most pronounced.

THE RELATION OF OPTICAL AND RADIATION PYROMETRY TO MODERN PHYSICS.

The following paper on "The Relation of Optical and Radiation Pyrometry to Modern Physics" was contributed by **Dr. Paul D. Foote**, of the Bureau of Standards, Washington.

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The practical science of optical and radiation pyrometry, which indirectly, in one manner or another, plays such an important rôle in our personal welfare and safety, has for its basis probably the most intricate theoretical foundation of any of the various phases of industrial physics. Precision work in this type of pyrometry involves a consideration of optics, physiological optics, statistical mechanics, thermodynamics, metallurgy, and chemistry of reactions at high temperatures. Only a few of the relations of radiation and optical pyrometry with other fields of physics are mentioned in the present paper.

Two fundamental laws of radiation form the basis of the theory of optical and radiation pyrometry. These are known as the Wien or Planck spectral distribution law and the Stefan-Boltzmann law of radiation. The derivation of the latter law is obtained from an application of thermodynamics. The derivation of the Planck spectral distribution law has led to the assumption of an atomic structure of energy. This assumption is the basis of the many interesting phases of the quantum theory. The use of these two equations in pyrometry, and the interrelation of their various constants with the constants of other important radiation laws, is of interest. The following five relations may be selected for consideration, in which the important constants are b, c_2, σ, h, and K.

(1) Wien displacement law—

$$\lambda_{max.}\theta = b = \frac{c_2}{4{\cdot}9651}.$$

(2) Stefan-Boltzmann law—

$$J = \sigma\theta^4 = \text{rate of emission of total energy.}$$

(3) Planck's distribution law—

$$J_\lambda = c_1\lambda^{-5}(e^{c_2/\lambda\theta} - 1)^{-1} = \text{rate of emission of energy comprised by radiation between } \lambda \text{ and } \lambda + d\lambda.$$

(4) Another form of Planck's law—

$$J_\lambda = \frac{2\pi c^2 h}{\lambda^5}(e^{ch/K\lambda\theta} - 1)^{-1}.$$

(5) Wien's law—

$$J_\lambda = c_1\lambda^{-5}e^{-c_2/\lambda\theta}.$$

Equation (2), the basis of radiation pyrometry, states that the energy radiated by a black body is proportional to the fourth power of its absolute temperature, θ. Equation (3) explains how the energy of radiation represented by the various wave-lengths is distributed throughout the spectrum of the black body. It is readily seen that for any given temperature the intensity of energy emission shows a maximum at some definite wave-length. The relation between the value of the wave-length at which a maximum emission of energy occurs and the absolute temperature of the black body radiator is given by equation (1). When the product $\lambda\theta$ is sufficiently small, Planck's law reduces to the simpler Wien's law, equation (5). This latter equation, the basis of optical pyrometry, states that for any definite wave-length (or colour) the brightness of a black body is proportional to $e^{-\text{constant}\,\theta}$. Equation (4) represents another form of Planck's law (3).

The constant b of equation (1) may be determined by observing with a spectrothermopile or bolometer the intensity of radiation at various wave-lengths emitted by a black body at a known temperature. The wave-length at which the energy intensity becomes a maximum multiplied by the absolute temperature of the black body gives the constant b. The most recent value for this is 0·2890 cm. deg. The constant is more accurately determined directly from the value of c_2.

The constant σ of equation (2) is defined as the rate at which energy of all wave-lengths is radiated from a black body 1 cm.^{2} in area to surroundings which are at a temperature one degree lower. This constant is determined by measuring the rate at which radiation from a black body at a definite temperature falls upon the receiver of a thermopile. The distance between the thermopile and the black body and the area of each must be known. The most recent work assigns a value to σ of $5{\cdot}7 \cdot 10^{-5}$ ergs sec.$^{-1}$ cm.$^{-2}$ deg.$^{-4}$.

The constant c_2 of equation (3) may be determined by observing the form of the spectral energy curve for a black body at any definite temperature. The intensity of the energy emission at various wave-lengths is measured by use of a spectral thermopile or bolometer, and the values so obtained are plotted against the wave-length. The method of computing these curves is somewhat involved. The most recent work indicates that $c_2 = 1{\cdot}435$ cm. deg.

Wien's law, equation (5), is applicable for work in the visible spectrum. If we measure the ratio of brightnesses, for a single wave-length, of two black bodies, one at a temperature θ_1 and the other at a temperature θ_2, the value of c_2 is given by the following equation obtained directly from Wien's law—

$$c_2 = \frac{\lambda \log (\text{ratio of brightnesses})}{\frac{1}{\theta_2} - \frac{1}{\theta_1}}.$$

Determinations of c_2 made in this manner by use of a spectrophotometer are in good agreement with the value of c_2 determined from the spectral energy curves.

Planck's equation may be written in the equivalent form, equation (4), where h is known as Planck's universal constant because it occurs in so many different formulæ of modern theoretical physics, especially in connection with various phases of the quantum theory. K is the gas constant reckoned for a single molecule. This constant also occurs in

the familiar gas equation $pv=n\mathrm{K}\theta$, where p is the pressure of an ideal gas, v the volume of n molecules, and θ the absolute temperature. There is accordingly an intimate connection between the various radiation constants and the constants concerned in the kinetic theory of gases. This interrelation of constants is still more involved, however, with certain electrical constants, such as the charge on an electron and the Faraday constant of electrolysis, as will appear immediately. We have from Planck's law—

$$\mathrm{J}_\lambda d\lambda=\frac{2c^2h\pi}{\lambda^5}(e^{ch\,\mathrm{K}\lambda\theta}-1)^{-1}d\lambda,$$

where c is the velocity of light. The integral of this equation gives the Stefan-Boltzmann law—

$$\mathrm{J}=\int_0^\infty \mathrm{J}_\lambda d\lambda=\frac{12\pi h}{c^2}\left(\frac{\mathrm{K}\theta}{h}\right)^4 . 1{\cdot}0823=\sigma\theta^4.$$

(6) Whence $$h=\sqrt[3]{\frac{4{\cdot}533\mathrm{K}^4 . 10^{-20}}{\sigma}}.$$

From the gas equation we have

(7) $$\mathrm{K}=\frac{pv}{n\theta}.$$

If we let the pressure $p=1$ atmosphere, $\theta=273{\cdot}1°$ abs., and $v=1$ cm.^{3} we can determine K from the number of molecules in a cubic cm. of gas under standard conditions. This may be obtained from the Faraday constant of electrolysis, the density and atomic weight of hydrogen, and the charge on an electron as follows :—

Number of atoms of H/cm.^{3} under standard conditions

$$=\frac{(\text{Faraday constant}) . (\text{density of hydrogen})}{(\text{Atomic weight}) . (\text{charge on electron})}$$
$$=\frac{(9{,}650)\,(0{\cdot}09004)\,3 . 10^{10}}{(1{\cdot}008)\,(4{\cdot}774) . 10^{-10}}=5{\cdot}416 . 10^{19}.$$

Whence number of molecules/cm.$^3=n=\frac{5{\cdot}416}{2}10^{19}=2{\cdot}708 . 10^{19}.$

Thus

$$\mathrm{K}=\frac{pv}{n\theta}=\frac{(1{\cdot}0137)10^6(1)}{(2{\cdot}708)10^{19} . 273{\cdot}1}=1{\cdot}372\ 10^{-16}\ \text{erg deg.}^{-1}.$$

Substituting this value of K in equation (6) we obtain

$$h=\sqrt[3]{\frac{(4{\cdot}533)\,(1{\cdot}372)^4\ 10^{-64}\ 10^{-20}}{5{\cdot}70 . 10^{-5}}}.$$

or

$$h=6{\cdot}556 . 10^{-27}\ \text{erg sec.}$$

Also by comparing the exponents of e in the two forms of Planck's law, equations (3) and (4), we find that

$$h=\frac{c_2\mathrm{K}}{c}=\frac{(1{\cdot}435)\,(1{\cdot}372)\ 10^{-16}}{3 . 10^{10}}=6{\cdot}563\times 10^{-27}\ \text{erg sec.}$$

The constant h may be determined in many other ways besides the use of Planck's law of radiation. Duane and Hunt proved experimentally that the voltage V required to produce X-rays of a given frequency ν is determined by the quantum relation $h\nu = eV$, in which e is the charge on an electron.

Millikan has determined h from a study of the photoelectric effect. Thus, when ultra-violet light falls on a metal, electrons are ejected, and the energy of emission of these electrons is given by the Einstein equation—

$$\tfrac{1}{2}mv^2 = Ve = h\nu - p,$$

where $h\nu$ is the energy absorbed by the electron from the exciting ultra-violet light, p is the work necessary to get the electron out of the metal, $\tfrac{1}{2}mv^2$ is the maximum energy with which the electron leaves the surface of the metal. The energy of the ejected electrons can be measured by applying to the surface of the metal a retarding positive potential V just sufficient to prevent the escape of the electrons. If the potentials required for various frequencies of the exciting radiation are plotted against these frequencies, a straight line is obtained, the slope of which is h/e.

Another method of determining h is by means of a study of ionization and resonance potentials for electrons in vapours of boiling metals. This method has been employed by the writer and others in the pyrometer laboratories of the Bureau of Standards. It is found that when electrons collide with atoms of metallic vapours the collision is usually elastic. That is, after collision the electron possesses the same kinetic energy which it had before collision. For certain velocities of the colliding electron, however, the collision is inelastic, and the electron gives all of its energy to the atom.

Two types of inelastic collision are known, one in which the energy of the electron goes over into an agitation of the electrons bound in the atom and produces a radiation of a single-line spectrum. For example, with mercury the single line $\lambda = 2{,}537$ Å. is emitted. The other type of inelastic collision results in the expulsion from the atom of a single electron. This latter phenomenon is known as ionization, for the atom as a whole, having lost at least one negative charge, becomes positive. Ionization is accompanied by the emission of the many-line spectrum of the metal in question. The velocities required to cause inelastic collision are developed by allowing the electrons to fall through an accelerating electric field. The potentials through which the electrons have to fall to produce these two types of collisions are known as the resonance potential and the ionization potential. These potentials are involved in the quantum relation $h\nu = eV$, where V is the above referred to potential and ν the frequency of the emitted radiation, in the case of a resonance collision. For a collision resulting in ionization ν represents a limiting frequency which is readily determined from spectroscopic data. If in the above equation we substitute the value for the electronic charge determined by Millikan, we obtain

$$h = \lambda V \, 0{\cdot}5304 \, . \, 10^{-30} \text{ erg sec.},$$

where V is measured in volts and λ is the wave-length in Ångström units of the radiation of frequency ν. The following table represents experimental data on ionization and resonance potentials for elements for which the value of λ is known with certainty—

TABLE I.

Ionization and Resonance Potentials.

Element.	Limiting Wave-length.	Observed Ionization Potential.	Observer.	Observed $h \cdot 10^{27}$.
Cd	1,378·69	8·92	Tate and Foote	6·52
Na	2,413	5·13	Tate and Foote	6·57
K	2,856	4·1	Tate and Foote	6·21
Zn	1,319·95	9·5	Tate and Foote	6·65
Hg	1,188·0	10·35	Tate, Davis, and Goucher	6·52
Mg	1,621·7	7·77	Foote and Mohler	6·68
	Single line	Resonance		
Cd	3,260·17	3·88	Tate and Foote	6·71
Na	5,893	2·12	Tate and Foote	6·63
K	7,685	1·55	Tate and Foote	6·32
Zn	3,075·99	4·1	Tate and Foote	6·69
Hg	2,537	4·9	Franck and Hertz, Tate	6·59
Mg	4,571	2·66	Foote and Mohler	6·45
			Mean ..	6·54 *

* $\pm$ 0·5 per cent. probable error.

The above values are plotted in Fig. 1, V versus $1/\lambda$. A straight line passing through the origin is obtained, confirming the quantum relation. The slope of this line is a measure of h. The mean value of h obtained from either this curve or the data in Table I is found to be

$$6{\cdot}54 \times 10^{-27} \text{ erg sec.},$$

with a probable error of 0·5 per cent. The universality of the important pyrometer constant h is illustrated by Table II, which presents a summary of recent determinations by various methods.

The relation of physiological optics to precision pyrometry has been recognized only within the past few years. One example, however, of its importance is sufficient to serve as an illustration. The high temperature scale of the United States Bureau of Standards, and other standardizing laboratories, is determined by measurements with an optical pyrometer of the Holborn-Kurlbaum type. A so-called monochromatic red glass of the highest quality is mounted in the ocular of this instrument, and the tip of the filament of the standard electric lamp is brought to a photometric match with the object sighted upon by varying the current through the lamp. In order to ensure permanence of calibration, this lamp is not operated above 1,300° C. For determining higher temperatures, an absorption glass is located between the pyrometer and the source sighted upon, thus reducing the observed brightness of the source. If the red glass were strictly monochromatic, the following relation obtained from Wien's law would apply, where θ is the absolute temperature of the black body source, S is the observed absolute tem-

perature using the absorption screen, and T′ is the transmission of the absorption screen for the wave-length λ defined by the red-glass ocular.

$$\frac{1}{\theta} - \frac{1}{S} = \frac{\lambda \log T'}{c_2 \log e} = A. \tag{8}$$

Since on the above assumption λ and T′ are definite constants, the second term of the above equation is equivalent to an experimentally determinable constant A. Hence, the reciprocal of the true absolute temperature of the furnace is equal to the reciprocal of the measured absolute temperature plus a certain negative constant A. Actually, however,

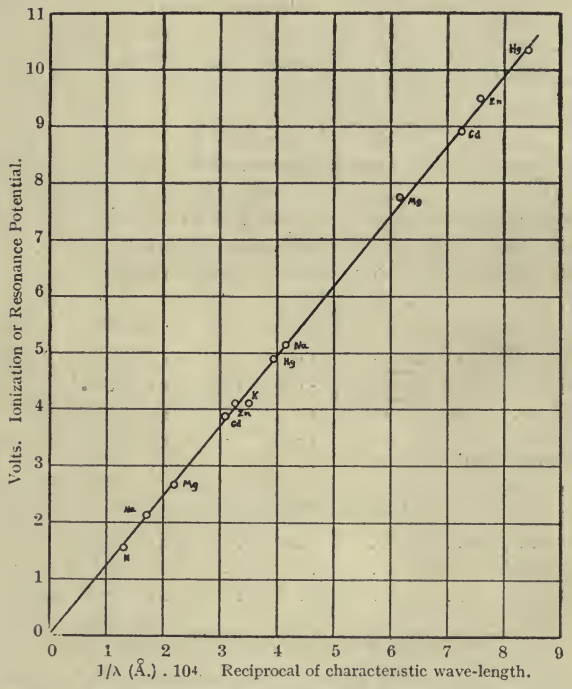


FIG. 1.—Determination of Planck's constant *h* by ionization and resonance potentials.

the red glass is not monochromatic, but transmits a band of red light. The question then arises as to the values which should be assigned to λ and T′. Moreover, the proper value to choose for λ is not a constant, but varies with the temperature of the source. A red glass which transmits a band of radiation tends to appear yellow as the temperature of the source increases. Also, if the ordinary black glass absorption screen is employed, its transmission T′ varies decidedly with λ, and hence with the temperature θ of the source. And finally, since the lamp is operated at a temperature different from that of the furnace, and since the red glass is not monochromatic, the photometric match between the lamp and the source viewed is not a colour match. Whence the subject of physiological optics is introduced and Wien's law as given above does not apply.

The eye possesses a different sensibility for light of different wave-lengths. The sensibility or visibility of the normal eye as a function of the wave-length of the exciting radiation has been determined by several investigators. Luminosity, L, of a heterochromatic source may be defined as the integral in respect to $d\lambda$ of the product of the visibility V_λ and the intensity J_λ of radiation of wave-length λ emitted by the source, thus—

$$\text{Luminosity} = L = \int_0^\infty V_\lambda J_\lambda d\lambda. \tag{9}$$

In the above example, the luminosity of the lamp at an absolute temperature S, as viewed through the red glass screen having a trans-

TABLE II.

Determinations of h.

Black Body Radiation.

Coblentz (from c_2 determined radiometrically) ..	$6{\cdot}56 \times 10^{-27}$ erg sec.
Coblentz (from σ ,, ,,) ..	6·56
Reichsanstalt (from c_2 ,, ,,)	6·54
Mendenhall (from c_2 determined spectro-photometrically)	6·59

X-rays.

Blake and Duane	6·56
Duane and Hunt	6·51
Hull	6·59
Webster	6·53
Webster and Clark	6·53

Photoelectric Effect.

Millikan	6·57
Kadesch and Hennings	6·43
Sabine	6·58 to 6·71

Ionization and Resonance Potentials.

Foote and Mohler, using data of Franck and Hertz, Tate and Foote, Foote and Mohler, Davis and Goucher, Tate	6·54

mission coefficient $T_\lambda = f(\lambda)$, is matched with the luminosity of the furnace at an absolute temperature θ, as viewed through the red glass screen having a transmission coefficient $T_\lambda = f(\lambda)$, and the absorption screen having a transmission coefficient $T'_\lambda = \phi(\lambda)$. The condition for a photometric match is given by equation (10), analogous to equation (9) above.

$$\int_0^\infty TT'VJ(\lambda, \theta)d\lambda = \int_0^\infty TVJ(\lambda, S)d\lambda. \tag{10}$$

This equation may be solved graphically for θ in terms of S, and it is convenient to express the relation in form (11)—

$$\frac{1}{\theta} - \frac{1}{S} = A(\theta). \tag{11}$$

The difference between equations (8) and (11) is that in the latter A is a function of the temperature of the furnace. It is found that A increases with increasing θ for the Jena black glasses and decreases with θ for a sector disk. If the consideration of the variation of A with the temperature of the source is neglected, errors amounting to 30° or 40° C. at 3,000° C. may result. It may be pointed out that the variation of A with θ is practically impossible to determine by direct experiment. An indirect method as outlined above is necessary. The direct determination of A requires two measurements, one of θ and one of S. The maximum value of θ permissible for such an experiment is about 1,500° abs., since the lamp filament deteriorates at higher temperatures. The minimum value of θ is high because the measurement of S must be above 1,000° abs. in order to obtain sufficient luminosity for an accurate setting. Hence the temperature range over which A can be determined by direct experiment is too small to give a definite idea of the relation of this factor as a function of the temperature of the source.

Equation (10) suggests that it is possible to choose an absorption glass such that A is independent of θ. It is readily seen, on the assumption that the pyrometer lamp is a black radiator, that the transmission curve of the absorption glass should have the form $T'_\lambda = e^{Ac_2/\lambda}$, where A is the desired constant, independent of θ. If a tungsten lamp is employed, the form of the transmission curve is altered somewhat, but is easily determinable. At the present time we are trying to select a combination of black and coloured glasses which will give the required transmissions with a high degree of precision.

Other interesting applications of physiological optics to pyrometry arise in the consideration of emissivity of non-black radiators, luminosity of metals, and colour temperatures. The question of statistical mechanics is of great importance in the measurement of flame temperatures. On the assumption that electrical conductivity is due to free electrons, it is possible to determine the number of free electrons per unit volume in a metallic radiator by measurements with the optical pyrometer combined with those of electrical resistivity. Some of the deductions from the Maxwell theory of light can be accurately verified by observations with the ordinary form of radiation pyrometer.

These few illustrations, among many others, may serve to suggest a justification of the statement made in the opening paragraph that the practical science of radiation and optical pyrometry is intimately connected with the most interesting phases of modern physics.

THE AUTOMATIC CONTROL AND MEASUREMENT OF HIGH TEMPERATURES.

Mr. Richard P. Brown (Philadelphia) presented a paper on "The Automatic Control and Measurement of High Temperatures," which was communicated by the Secretary.

Some of the instruments referred to in the paper were exhibited by Messrs. Hadfields, Limited, and described by **Mr. S. A. Main** (see p. 158).

Probably no employee has caused the average works manager to have so many sleepless nights as the furnace-man, on whose shoulders rests the responsibility for the accurate heat treatment of the steel and the uniformity of the product. This is not only true of a steel plant, but is also equally true in the chemical industry, where the temperature of numerous processes must be accurately controlled; in the glass industry, where the melting of the glass and its annealing must be carried on within very narrow limits of temperature; in the brick industry, where the kiln firing is of the utmost importance; and I might continue the list throughout the whole industrial field.

The old furnace-man, through years of practice, will endeavour to gauge the temperature of the furnace with his eye. Providing he has not been up all the previous night, and his eye is clear, he will probably judge the temperature fairly accurately. If he is of a reasonably kindly disposition, he may permit the manager to instal pyrometers to guide him in controlling the temperature, and he may even in time use the pyrometers and rely on them.

But we can pardon the works manager for thinking, "Suppose John dies, gets sick, or quits his job, how am I to handle the output of these furnaces?" He would like to have an understudy for the old furnace-man, but the latter does not like the idea. So he wonders why some one does not develop a device to control automatically the temperature of the furnaces, so that he can cease worrying about them.

This is one reason why a great amount of study has been given, not only to the perfection of pyrometers, but also to the automatic control of temperature. It has, however, been only recently that real results have been accomplished in automatic temperature control.

First of all it was necessary to perfect the temperature-measuring instruments, so that they could be relied upon to indicate uniformly the actual furnace temperature. It was then necessary to apply to the pyrometers attachments to throw the switches on the electric furnaces, or open or close the valves on gas or oil furnaces.

My experience in the United States has shown that for industrial service an instrument actuated by the expansion of nitrogen gas is the most satisfactory for temperature measurements up to 800° F. or 425° C. The gas expansion instrument consists of a bulb of copper which is

inserted in the heat, and this bulb is connected by capillary tubing to an indicating or recording gauge containing a helical expansive spring.

The expansion of gas in the bulb exerts a pressure in the capillary tubing, which is conveyed to the spring in the instrument, and the pointer attached directly to this spring moves across the scale or chart.

It is essential in this instrument that the capacity of the bulb be some fifty times as great as the capacity of the capillary tubing and spring. This is essential so as to reduce to a minimum errors due to atmospheric changes in temperature along the capillary tubing or at the instrument. In consequence this instrument is not desirable for use where the gauge must be placed more than 100 ft. from the bulb.

For use at moderate temperatures, where the measuring instrument must be placed at a considerable distance, and for temperatures above the range of the gas expansion instrument, the thermoelectric pyrometer has been almost universally adopted in the United States. A thermocouple of base metals, usually formed of one wire of nickel 90 per cent., chromium 10 per cent., and the other wire 98 per cent. nickel and 2 per cent. aluminium, is preferred for temperatures to 1,800° F. or 1,100° C. For temperatures above this, and as high as 2,800° F. or 1,500° C., thermoelectric pyrometers using a platinum-rhodium thermocouple are the most satisfactory. For higher temperatures still, a radiation type of pyrometer is available, consisting of a thermocouple in the focus of a reflector at the end of the tube, which is pointed at the door or opening of the furnace.

For measuring the voltage produced by a thermocouple, whether of base metal, platinum-rhodium, or the radiation type, high-resistance milli-voltmeters are available. Such milli-voltmeters are produced by us in the United States, of some 1,000 ohms or more. This remarkably high resistance is naturally desirable to practically eliminate the errors due to changes in the resistance of the line or wiring connecting the thermocouples and the instrument, and also to nullify the effects of any changes in the resistance of the thermocouples, due to heating.

Changes in resistance may be due to actual changes in length or changes in atmospheric temperature, which in turn affects the resistance of the line or wiring. We have been able to secure this exceedingly high resistance by reducing the weight of the moving element to a minimum, and I have a sample of this moving element for exhibition.

The total weight of the moving element in our high-resistance pyrometer, including pointer and springs, is 526 mgms. This extreme lightness is secured by the use of an aluminium alloy wire which we have succeeded in enamelling. The enamel coating is much thinner than the silk insulation formerly used, and more turns can be secured on a coil of a given width. Likewise, by the use of the aluminium wire the weight has been reduced 66⅔ per cent. as compared with copper wire which was formerly used for these moving elements. The aluminum wire is ·003 in. in diameter, and drawing this wire has been quite a mechanical problem.

The pointer tubing in this moving element is of aluminium with an inside diameter of ·008 in. and an outside diameter of ·012 in., or a total thickness for the wall of the tubing of ·002 in. Even this weight for the pointer tubing could probably be reduced by the use of magnesium instead of aluminium, but to date we have been unable satisfactorily to draw magnesium.

I only cite these points regarding the construction of our present-day high-resistance pyrometer milli-voltmeter to show what development

work can produce. Instruments of this type made by Siemens and Halske of Germany were never developed to this extent, at least prior to the outbreak of the war, and their moving element was several times as heavy as the sample I have here, and in consequence the resistance of their pivoted meter was several times less. Incidentally, I think we have about reached the limit of development work along this particular line.

It will be understood that the same electrical system, such as I have described, can be used either to indicate the temperature, or combined with the proper apparatus to record the temperature constantly on a recording sheet. There are both portable and wall type indicating pyrometers, and recording pyrometers are produced to make a record on a circular 8-in. chart, or to make a continuous record of the temperature on a roll of paper lasting two months or more. By the introduction of suitable switching mechanism a record of the temperature of quite a number of thermocouples can be made on the same record sheet. These temperature records are distinguished by using different colours for each record line, by using numbers corresponding to each thermocouple, or changing the form of line produced on the chart for identification.

For even greater precision in temperature measurements than is secured with the high-resistance milli-voltmeter, I have developed a new instrument, which we call the Brown Heat Meter. This instrument is suitable for either temperature measurement or automatic control of temperature, and a brief description of this new instrument may be of interest.

My idea in the heat meter has been to eliminate all the bad features or drawbacks met with in using a milli-voltmeter for temperature measurement.

Possible sources of error in the use of a milli-voltmeter in temperature measurements, even one of high resistance, consist in changes in resistance of the circuit comprising the thermocouple and the leads or wiring, due to changes in length or atmospheric changes in temperature; errors also can occur due to temperature coefficient of the meter—that is, errors caused by atmospheric changes in temperature of the meter itself. Another source of error is a change in the actual indication of the instrument, due to spring fatigue, abuse or sticking, and to overcome these possible sources of error we have developed this rather interesting instrument.

Briefly, its operation is as follows :—

With our standard milli-voltmeter of high resistance, we supply an ordinary dry cell about 1¼ in. in diameter by 2½ in. long, and furnish suitable rheostats to reduce the voltage of the dry cell from approximately 1½ volts to a range from 0 to 60 milli-volts, the voltage produced as a maximum by the thermocouples.

In our first operation, we oppose the voltage developed by the thermocouple to the reduced voltage of the dry cell, and when the pointer stands on zero, it indicates that the voltage from each source is equal. We now put in operation No. 2 cut-out with a switch the voltage of the thermocouple and read the voltage of the dry-cell circuit by direct deflection. This eliminates the line resistance entirely as in a potentiometer.

We have now a deflection indicating the actual temperature developed by the thermocouple at the moment of reading the instrument, but fluctuations in temperature of the thermocouple will not be indicated, as we are reading the voltage from the dry cell. We have, however, incorporated other operations in this meter.

In operation No. 3 we connect the thermocouple to the meter instead of the dry-cell circuit, and we note whether the indications are the same;

By switching back and forth quickly, the voltage from the thermocouple circuit or from the dry-cell circuit can be noted. If excessive line resistance has caused the indications of the milli-voltmeter to be lowered as compared with the dry-cell circuit, a rheostat is operated to bring up the indications of the thermocouple circuit to that shown when we are reading the voltage of the dry-cell circuit.

We now leave the instrument indicating on the thermocouple circuit. The errors, if any, which may be due to line resistance or changes in temperature of the line have been eliminated, and we have a direct reading milli-voltmeter, indicating the correct temperatures.

A rheostat is supplied in the meter of 15 ohms, which permits of adjusting the indications for a total change of line resistance equivalent to 15 ohms, or a circuit of two copper wires almost a mile long.

We have eliminated the temperature coefficient of the meter by furnishing a copper resistor in the meter equivalent to the copper or aluminium of the coil; hence in balancing the voltage from the dry cell against that of the thermocouple we also automatically eliminate errors due to the temperature coefficient of the meter itself.

There is now left only one possible source of error, the change in the actual indications of the meter due to sticking of the pointer, abuse of the instrument, spring fatigue, etc. To obviate this source of error, we can supply with the instrument a standard cell with suitable resistors, and in the same manner as the meter can be tested by the potentiometer method we can check this meter. We supply three resistors, for example, where a meter is calibrated for 60 milli-volts, namely, resistors equivalent to a deflection of 20, 40, or 60 milli-volts on the scale, and after balancing the standard cell against a part of the voltage of the dry cell, through these suitable resistors we can note whether the pointer swings to 20, 40, and 60 milli-volts respectively on the scale. If it does not, the error can be noted and the actual error in calibration is detected.

Where the instrument is supplied with a standard cell, the temperature of the instrument should always be between 5° C. and 40° C., or 40° F. and 105° F.; in fact, standard cells of cadmium sulphate or zinc sulphate will be injured if the temperature rises or falls beyond these limits. This is true of any standard cell employed in instruments.

In this instrument we have all the good features of the potentiometer method of measuring temperature with the advantage that we have a direct-reading instrument which can be adjusted once every day or oftener if desired, for the actual line resistance with which it is used, and under the surrounding atmospheric conditions. The meter will then indicate correctly throughout the whole scale range, and the furnace-man has the instrument to guide him without hand manipulation, and an inspector can daily check the calibration of the instrument.

Naturally, this instrument is equally suitable for automatic temperature control as the instruments previously described when properly designed for this service.

Automatic Temperature Control.

Attempts have been made in the past to operate switches and valves electrically by permitting the pointer of the pyrometer to come in contact with adjustable contact arms on each side of the pointer. Unfortunately the milli-voltmeter, used with the thermoelectric pyrometer, has an exceedingly weak control for the pointer. One is easily able to blow the pointer across the scale with the breath.

In consequence, simply permitting the pointer of such a pyrometer to move into contact is not sufficiently positive to be satisfactory for automatic control work.

The automatic control pyrometer exhibited here operates in the following manner: A thermocouple formed of a nickel-chromium alloy is installed in the electric furnace, the temperature of which is being controlled. The thermocouple actuates a high-resistance milli-voltmeter. Below the pointer, and adjustable throughout the whole scale range, is a table carrying two contact pieces, separated by a thin piece of insulating material $\frac{1}{32}$ in. thick. The depressor arm driven by a small electric motor, or by a clock if preferred, depresses the pointer at regular intervals, usually every ten seconds, and in doing so the pointer forces together the two contact pieces below.

Let us assume the pyrometer controller is required to control the furnace at a temperature of exactly 1,400° F. The knob on the left of the instrument is turned until the index in front of the scale stands at 1,400° F. This index corresponds to the position of the thin insulating material which separates the high and low contacts.

The switch connecting the furnace in the line is closed, and the pointer slowly rises across the scale as the temperature of the furnace rises. As the switch is already closed, when the pointer is depressed on the low contact, the switch continues to remain closed, and no change occurs until the pointer passes over the neutral insulating piece and is depressed on the high contact. The switch, indirectly operated by a solenoid, and relay are now instantly actuated and the circuit opened. The temperature of the furnace begins to slowly fall, and when the pointer is again depressed on the low contact, the circuit is again closed. This operation continues as long as the furnace is to be operated.

When the switch opens and closes the main circuit, the current in consequence is either full on or off, and the fluctuations are continuous within narrow limits of some 10° to 20° F. These continuous risings and fallings of temperature can be largely reduced, and closer control can be procured by the use of two rheostats in the furnace line. The solenoid operated automatic switch is then used simply to cut in and out of circuit the second rheostat.

Assuming it is desirable to maintain continually 1,400° F. in the electric furnace, irrespective of fluctuations of voltage, the two rheostats are set so that with only one rheostat in the circuit the temperature will rise to approximately 1,500° F. With the second rheostat in the circuit the temperature drops to 1,300° F.

When we now use the solenoid-operated switch to cut in and out the second rheostat, we naturally control the temperature only between 1,500° and 1,300° F., and we do not have the rapid surges or ups and downs in temperature, and maximum control is secured.

It is realized that the same form of switch can be used to operate a valve to control a gas or oil furnace. We have found it desirable to use an automatic valve in a by-pass so as simply to control a portion of the gas or oil supply, and in the same manner as in the electric furnace control, eliminate the maximum fluctuations caused by the complete opening and closing of the switch or valve.

Assuming that we have a 2-in. supply pipe for the gas to the furnace, it is customary for us to by-pass this and use a ½-in. automatic valve, which gives us approximately 25 per cent. control. This is sufficient to control the usual fluctuations in gas supply, and secures very

satisfactory control. This method also eliminates the difficulty which would occur where the gas is completely shut off and then turned on in full, as would occur without the by-pass control.

Temperature Signalling Pyrometer.

In addition to an instrument to automatically control furnace temperature, there has been a demand for an instrument to signal automatically by lights whether the temperature is too high, correct, or too low in any particular furnace.

It has been common practice in plants in the United States, where there are a number of heat-treating furnaces, to maintain an operator at a central pyrometer, and by coloured electric lights at the furnace to signal whether the temperatures are right or not. It is common practice to locate three lights above each furnace—red, white, and green; the red light burns when the temperature is too low, the white light when the temperature is within certain limits—for example, 20° F. of the correct temperature—and the green light burns when the temperature is too high. The fireman who operates the furnace is guided entirely by the lights, and a central pyrometer is used to control the temperatures.

We have been able to develop an instrument to signal automatically whether the temperature is correct or not by lights, and in this way the services of the operator at the instrument are eliminated. The same form of instrument is used for this purpose as we use to control automatically the furnace temperatures, and the pointer is depressed at intervals of every ten seconds on to contacts corresponding to the red, white, and green lights.

No special battery or other source of current than an ordinary service line is required to operate these lights. The supply may be 110 or 220 volts, either alternating current or direct current. The current which lights the lamps does not flow through the instrument, but is made and broken by an auxiliary device containing the necessary mechanism. A high resistor is in series with the circuit connected with the pyrometer, which reduces the current flowing through the contactors within the instrument to less than ·07 ampere. This prevents sparking at the contactors and errors due to the heating effect of a current of higher amperage. The lamps may be any reasonable distance from the pyrometer; in fact, they are operative at a mile or more if desired.

The various thermocouples in each furnace are connected successively to the instrument through switching mechanism, and at the same time a switching mechanism connects the various sets of lights at each furnace. We have constructed an instrument of this character to take care automatically of signal lights at twelve furnaces.

This form of equipment gives the operator of the furnace an indication by lights which he can easily understand, and he adjusts the valves or fires the furnaces accordingly. It is a simple method to instruct a man to keep the white lights burning and to explain what the red and green lights mean, and a less experienced workman can control the furnaces in this manner than where one is required who can read temperatures on a pyrometer scale. This newly developed instrument also eliminates the man to read the temperatures at the central pyrometer.

The extensive use of pyrometers to measure or record high temperatures will serve (1) to eliminate guesswork as to the temperature; (2) to reduce fuel consumption through the maintenance of the correct temperature

and not excessively high temperatures; (3) to reduce time for heating of the product due to the maintenance of the correct temperature; (4) to increase efficiency in operating a plant through the savings outlined above.

Instruments to control automatically the temperature, when properly constructed and applied, will eliminate entirely the personal element. The maintenance of the correct temperature in the furnace is automatic, and this is one step further, and in consequence an improvement over temperature control through pyrometers.

I do not doubt but that the next few years will see further improvements in pyrometers and temperature control. There will always be room for improvement, and the co-operation of the industrial works and the pyrometer manufacturers will largely hasten the development of practical instruments for the measurement and control of high temperatures.

THE ADVANTAGE OF BURYING THE COLD-JUNCTION OF A THERMOCOUPLE AS A MEANS OF MAINTAINING IT AT A CONSTANT TEMPERATURE.

Mr. Robert S. Whipple, M.I.E.E. (Cambridge), read a paper entitled "The Advantage of Burying the Cold-junction of a Thermocouple as a Means of Maintaining it at a Constant Temperature."

In March, 1903, Professor Anthony Zeleny, of the University of Minnesota, Minneapolis, suggested the advisability of burying the cold-junction of a thermocouple circuit as a means of maintaining it at a constant temperature.*

Although thermocouples have been frequently buried for the purpose of measuring earth temperatures, yet they have not, as far as I know, been buried for the purpose of maintaining the cold-junction of a thermo-electric circuit at a constant temperature. In the research laboratory, where accuracy is aimed at, it is customary to immerse the cold-junction in melting ice. As it is generally difficult to maintain an ice vessel near a furnace, this necessitates the placing of the ice vessel some distance from the source of heat. In the laboratory, where the cost of the wires for the rare-metal thermocouples was not very serious and where the furnace employed was small, this was not a matter of great importance; but in the works, where a large number of couples are used and where long lengths of leads are required, the employment of melting ice is impossible. The difficulty has been overcome to some extent by the use of thermos-flasks, and it is now no uncommon sight to see an installation of thermos-flasks mounted near the furnaces of a large works. In practice the flasks are filled with oil, in which the cold-junction of the thermocouple circuit, together with a mercury thermometer, are immersed, the thermometer being a ready means of showing the temperature of the oil. Experience shows that in the majority of cases the daily temperature range indicated by the mercury thermometer does not exceed 2° C., although the daily temperature range of the air surrounding the flask may amount to 10° or 15° C.

The introduction of Peake's compensating leads † has rendered it possible to transfer the cold-junction of a platinum, platinum-rhodium or iridium couple to a considerable distance from the head of the pyrometer, so that the employment of a buried cold-junction with the rare-metal couples is rendered commercially possible.

The high price of platinum and its alloys has compelled the use of base-metal thermocouples, and the reliability of some of the modern

* United States Patent Specification No. 721,770, March 3, 1903.

† See British Patent Specification No. 370, 1909, and "Methods of Measuring Temperatures," by R. S. Whipple, *Proc. Inst. Mech. Eng.*, 1913, p. 729.

MEAN SOIL TEMPERATURES (° C.) FOR EACH MONTH.

		CAMBRIDGE, at a depth of 10 ft. below floor of building.	GREENWICH, at a depth of 12·8 ft. below the unprotected soil.	
1911.	July	12·48	12·12	
	August	12·96	13·84	
	September	13·80	14·61	—Above.
	October	13·80	14·17	—Above.
	November	13·38	13·17	
	December	12·92	11·76	
1912.	January	12·53	10·57	
	February	12·05	9·53	
	March	11·89	9·11	
	April	11·96	9·24	
	May	11·97	9·93	
	June	11·97	11·07	
	July	11·99	12·39	
	August	12·77	13·55	
	September	12·95	13·67	
	October	12·95	13·07	
	November	12·86	12·19	
	December	12·62	11·00	
1913.	January	12·20	10·18	
	February	11·81	9·42	
	March	11·69	8·82	
	April	11·53	8·71	
	May	11·46	9·17	
	June	11·71	10·59	
	July	12·18	12·12	
	August	12·69	12·91	
	September	13·02	13·47	
	October	13·35	13·50	
	November	13·26	12·92	
	December	13·07	11·82	
1914.	January	12·77	10·46	
	February	11·97	9·36	
	March	12·45	8·88	
	April	11·97	8·77	
	May	11·99	9·41	
	June	12·20	10·62	

MAXIMUM TEMPERATURES (° C.) IN EACH YEAR.

	CAMBRIDGE. Temp. and Month.	GREENWICH. Temp. and Month.
July, 1911–June, 1912	13·80 Sept. & Oct.	Above 14·61 Sept.
July, 1912–June, 1913	12·95 Sept. & Oct.	13·67 Sept.
July, 1913–June, 1914	13·35 October	13·50 Oct.

MINIMUM TEMPERATURES (° C.) IN EACH YEAR.

	CAMBRIDGE. Temp. and Month.	GREENWICH. Temp. and Month.
July, 1911–June, 1912	11·89 March	9·11 March
July, 1912–June, 1913	11·46 May	8·71 April
July, 1913–June, 1914	11·97 Feb. & April	8·77 April

elements, such as (1) nickel, nickel-chromium, (2) iron, nickel-copper, or (3) copper, nickel-copper, justifies the use of these elements to a high degree of accuracy. The materials mentioned are not expensive, and at once open up the possibility of burying as a means of maintaining the constancy of the temperature of the cold-junction.

In connection with some experimental work at the Cambridge Scientific Instrument Company, it was desired to maintain a cold-junction at a constant temperature for a long period of time, and in July, 1911, one junction of a thermocouple was buried. The method of doing so may be of interest. A spot was selected in the floor of the test-room,

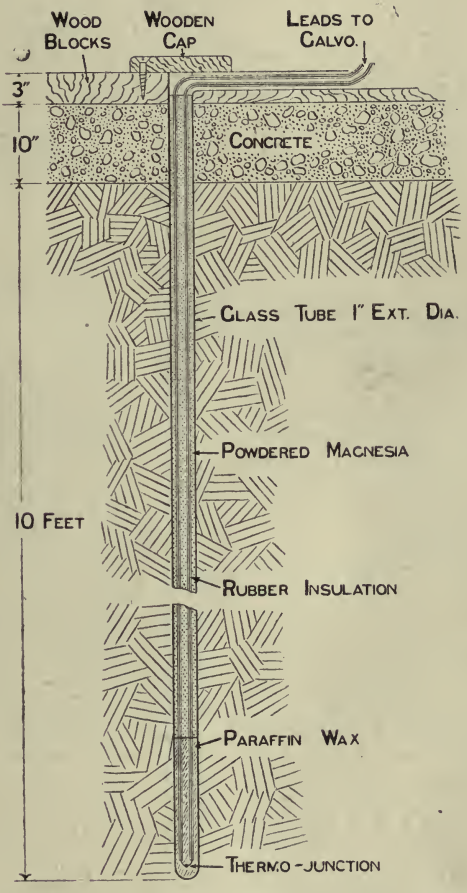


FIG. 1.—Method of burying Thermocouple under Test-room Floor.

as near the centre as possible, and a hole driven through the floor to a depth of 10 ft. The ground having been made up about thirty years before, this was a comparatively easy matter. A copper-constantan (60 Cu–40 Ni) couple connected to copper leads was placed in a glass tube 10 ft. long, paraffin wax having been run into the bottom end of the tube for a depth of 18 in., and the remainder filled with powdered magnesia. The tube was then lowered into the hole, and, the ground being made-up soil, it immediately closed round the tube; indeed, some

little difficulty was experienced in putting the tube in, owing to the soil continually falling into the hole. The four wires projecting from the open end of the tube, those forming part of the thermocouple and the copper leads respectively, were taken to terminals in the form of two lead-covered cables. It is thus possible to connect any thermocouple having the same thermal constants to the buried one. The details of the arrangement are shown in Fig. 1.

For a period extending over two years—July, 1911, to July, 1913—the electromotive force given by the couple was measured once a week by means of a potentiometer, the other junction of the circuit being

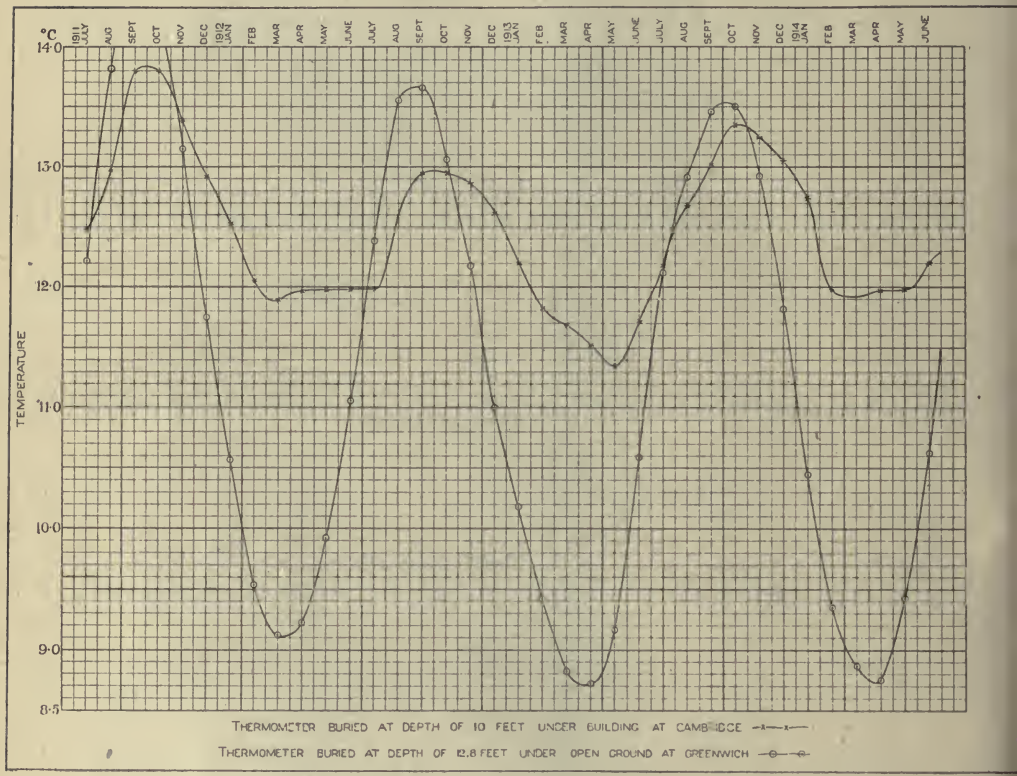

°C
14·0
13·0
12·0
11·0
10·0
9·0
8·5
TEMPERATURE
1911 JULY AUG SEPT OCT NOV DEC 1912 JAN FEB MAR APR MAY JUNE JULY AUG SEPT OCT NOV DEC JAN FEB MAR APR MAY JUNE JULY AUG SEPT OCT NOV DEC 1914 JAN FEB MAR APR MAY JUNE
THERMOMETER BURIED AT DEPTH OF 10 FEET UNDER BUILDING AT CAMBRIDGE
THERMOMETER BURIED AT DEPTH OF 12·8 FEET UNDER OPEN GROUND AT GREENWICH

FIG. 2.—Mean Soil Temperatures, July, 1911, to June, 1914.

immersed in melting ice. During the period August, 1913, to June, 1914, the temperature of the couple was read at longer intervals of time, generally once a month. By the courtesy of Sir Frank Dyson, the Astronomer Royal, I am able to publish the monthly values given by a mercury-in-glass earth thermometer buried at a depth of 12·8 ft. at the Royal Observatory, Greenwich, over the same period. The values for the two sets of observations are shown in the table opposite, the values being shown graphically in Fig. 2.

It will be seen that the rise and fall in temperature at the autumnal and vernal equinoxes is clearly marked, even in the couple buried under the building. In the case under discussion, the tube in which the couple

is buried is situated about 10 ft. from the exterior walls of the building. If, however, this distance could be made greater, it might, I think, be safely assumed that the temperature range would be less. It will be noticed that the times of maximum and minimum temperature agree with the Greenwich ones, but that, although the Greenwich thermometer is at a depth lower by 2·8 ft., yet the temperature range is approximately 3·5° C. greater than that shown by the buried junction. This is not surprising when it is considered that in the one case the ground above the thermometer is exposed to the weather, and in the other it is protected by means of the building.

The following are the extreme ranges of temperature (° C.) for the period under discussion—

	Cambridge.			Greenwich.		
	Max.	Min.	Range.	Max.	Min.	Range.
July, 1911–June, 1912 ..	13·80	11·89	1·91	Above 14·61	9·11	5·50
July, 1912–June, 1913 ..	12·95	11·46	1·49	„ 13·67	8·71	4·96
July, 1913–June, 1914 ..	12·35	11·97	1·38	„ 13·50	8·77	4·73
	Mean ..		1·59	Mean ..		5·06

In a paper * recently published by Dr. Arthur Rambaut, the Director of the Radcliffe Observatory, Oxford, he discusses the results of temperatures obtained by underground thermometers at Oxford during the years 1899 to 1910, and shows that the maximum temperature range of the thermometer buried at a depth of 9 ft. 11½ in. below the surface is 6·88° C., varying from 14·42° C. in September, 1899, to 7·54° C. in March, 1909. From the mean monthly temperatures over the same period the extreme range is 5·15° C., viz. from 13·26° C. in September to 8·11° C. in March. This value is almost identical with that obtained from the Greenwich thermometer buried at 12·8 ft. In the paper mentioned, Dr. Rambaut shows that at a depth of 66 ft. in Oxford gravel the temperature would remain sensibly constant throughout the year, i.e. the variation would not exceed 0·01° C. He shows also that at 45 ft. the amplitude is 0·1° C., so that an increase of 21 ft. in depth divides the amplitude of temperature range by 10. At Cambridge, therefore, if the law of diminution is the same, the range of 1·6° C. at 10 ft. would correspond with 0·16° C. at 30 ft. and with 0·016° C. at 50 ft. Thus, to obtain almost absolute uniformity of temperature at Cambridge, it would be necessary to go down as low as 50 ft. In the case under discussion it is almost certain that, as this depth would be well below the river level, any deductions of this kind are unreliable. The phase agreement between Greenwich and Cambridge is rather remarkable when it is considered that the thermocouple is under a building, and can only be 3 or 4 ft. above the high-water level of the Cam.

The question of uniformity of underground temperatures is also complicated by rainfall. Professor H. L. Callendar has shown † in one of his papers on soil temperatures that rainfall is found to raise the value of the diffusivity of the soil very considerably. An abnormal rainfall

* "Underground Temperature at Oxford as determined by means of Five Platinum Resistance Thermometers, November, 1898–October, 1910," by A. A. Rambaut, Sc.D., F.R.S., *Radcliffe Observations*, vol. li.

† "Preliminary Results of Observations of Soil Temperatures with Electrical Resistance Thermometers, made at McDonald Physics Buildings, McGill University, Montreal," by H. L. Callendar, M.A., F.R.S., *Transactions Royal Society of Canada*, Section III, 1895, p. 11,

may therefore cause a break in the constancy of temperature in a long series of readings. The larger the area of the floor of the building under which the buried couple is placed, the less will be the likelihood of rainfall affecting the constancy of the soil temperature below it. As the subject is of some interest, and the test-room at the works is now being increased in area, the opportunity is being taken to bury a thermocouple at a

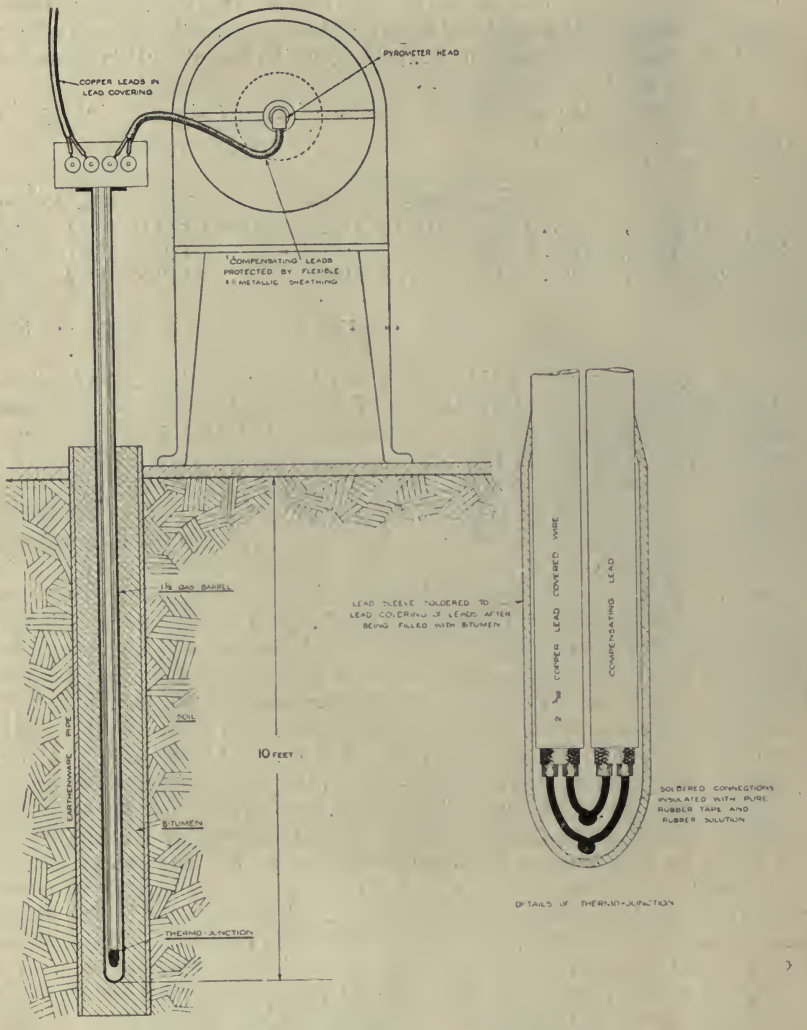

PYROMETER HEAD
COPPER LEADS IN LEAD COVERING
'COMPENSATING' LEADS PROTECTED BY FLEXIBLE METALLIC SHEATHING
1½ GAS BARREL
SOIL
10 FEET
BITUMEN
THERMO-JUNCTION
LEAD SLEEVE SOLDERED TO LEAD COVERING OF LEADS AFTER BEING FILLED WITH BITUMEN
2 COPPER LEAD COVERED WIRE
COMPENSATING LEAD
SOLDERED CONNECTIONS INSULATED WITH PURE RUBBER TAPE AND RUBBER SOLUTION
DETAILS OF THERMO-JUNCTION

FIG. 3.—Method of burying Thermocouple in a Works.

depth of 20 ft. in the centre of what will be a much larger building. It is hoped that on some future occasion it will be possible to publish the results obtained.

The buried couple has proved successful in works practice, and it may be of some interest to show the method of burying the couple in one of the most successful installations. This method is illustrated diagrammatically in Fig. 3.

FIG. 4.—Tube containing the Cold-Junction as a Complete Unit driven into the Soil.

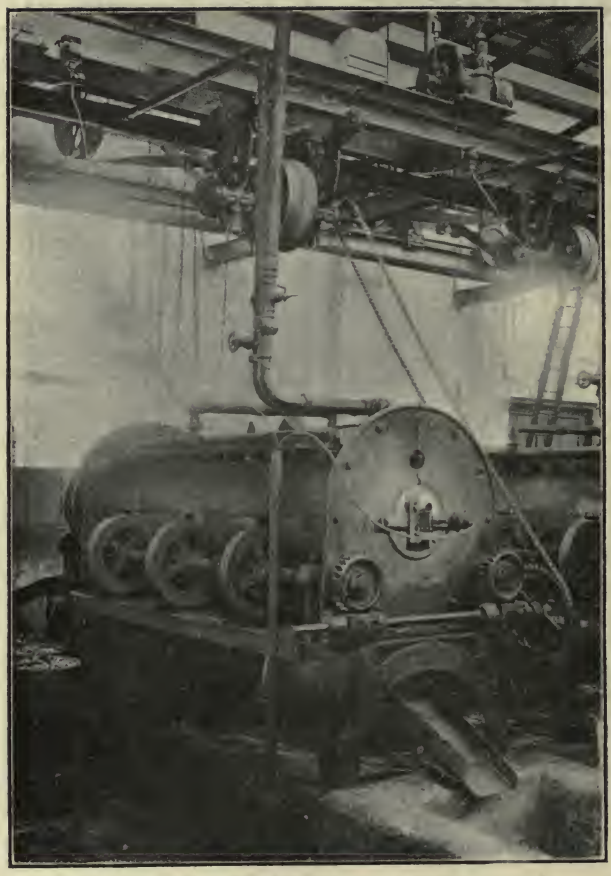


FIG. 5.—Buried Thermocouple in use in a Works.

A steel tube closed at one end is buried in a small earthenware drain-pipe to a depth of 10 ft., the space between the pipe and the tube being filled with bitumen. The copper lead wires are soldered to the compensating leads or other leads from the thermocouple, thus forming the cold-junction of the circuit. The joint is protected by an insulating material, such as bitumen, and a lead cap soldered to the outer lead sheathing protecting the thermometer wires. The two cables are then pushed to the bottom of the buried steel tube, the tube as far as possible being filled up with either hot bitumen or powdered magnesia. It is sometimes convenient to fit terminals on the head of the tube in which the cold-junction is buried, as shown in Fig. 3, or to construct the cold-junction arrangement in the form of a thermometer in which the protective sheath is driven into the ground. Such an arrangement is illustrated in Fig. 4, which I am enabled to reproduce by the courtesy of Mr. G. S. Heaven, of Messrs. White and Poppe. Buried junctions are being used by this firm in connection with an installation of thermocouples measuring temperatures in an explosives factory. The arrangement shown in Fig. 5 is slightly different, in that the cables from the buried couple run direct to the couple placed in the furnace and to the temperature indicators without the interposition of any terminals. I am indebted to Mr. Frank and Mr. Kievits, of Messrs. Kynoch, Ltd., for their courtesy in allowing me to reproduce the method of burying the cold-junction of their thermocouples, as illustrated diagrammatically in Fig. 3. As showing the efficiency of the method in works practice, I may mention that Mr. Kievits informs me that over a period of six months it was found that the temperature of the soil did not vary by more than 1·5° C.

In conclusion, it may be stated (1) that the temperature of the cold-junction of a thermocouple system, if buried to a depth of 10 ft. beneath the floor of a fairly large building, will remain constant to within less than 2° C. throughout the year ; (2) that if Peake's compensating leads are used with platinum-platinum-rhodium couples there is no practical difficulty in using the buried cold-junction in a works. If base-metal couples are used, the problem is even less complicated, as simpler means of protecting the couple can be employed, the couple generally being more robust and the accuracy required being of a slightly lower order.

DISCUSSION

At this stage the **Chairman** called for discussion on the group of papers which had been read, which were of a more general character than those to follow. He asked whether anybody present had had experience of the type of furnace described by Dr. Northrup.

NOTE ON THE WIBORGH PYROMETER.

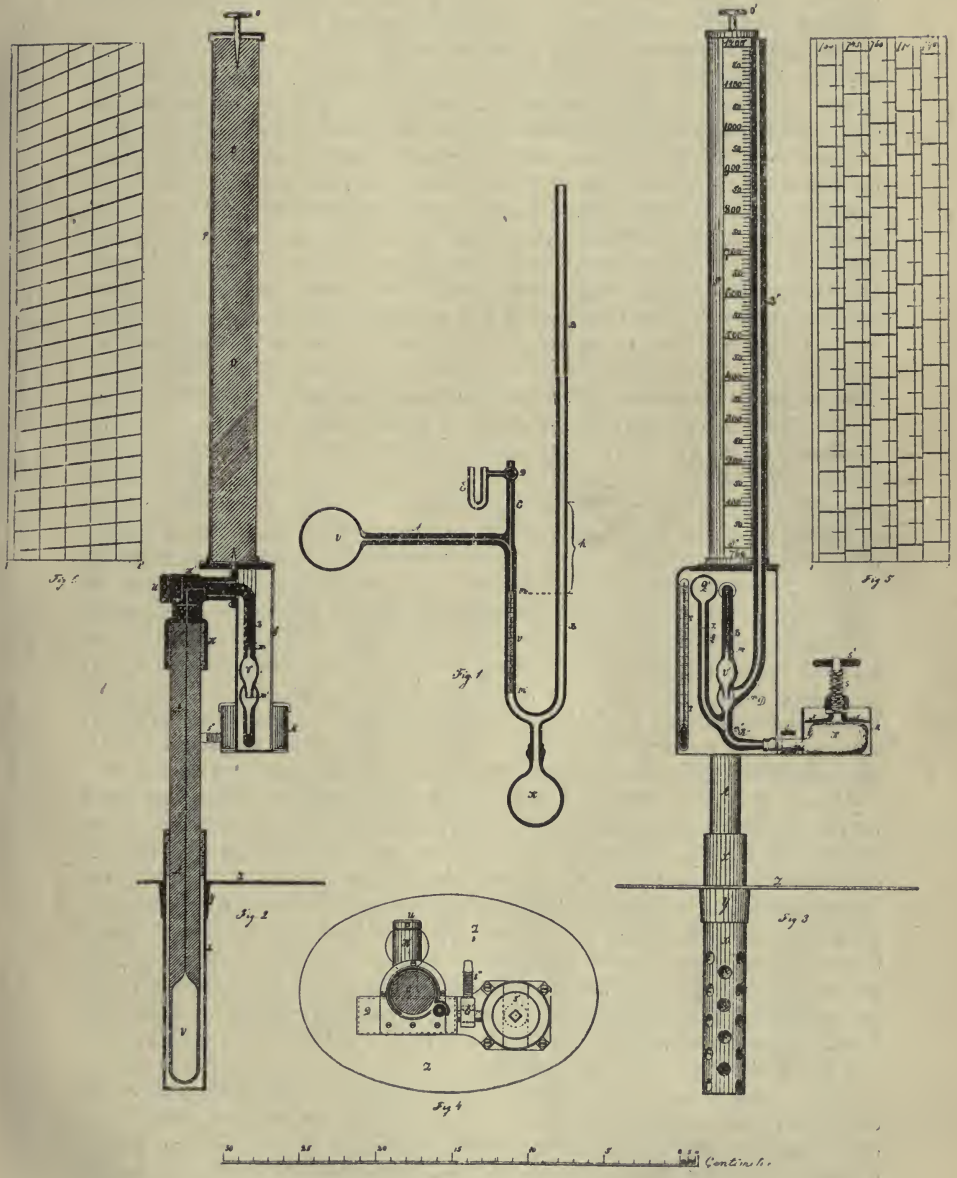
In the course of the discussion **Mr. John G. A. Rhodin, F.I.C.,** referred to the **Wiborgh Pyrometer.** The following description was subsequently communicated.

I had the pleasure of mentioning Professor Wiborgh's pyrometer during the discussion, but as nobody seemed familiar with the instrument, I decided to send in a short description of this highly ingenious instrument. It was first described in *Fernkontorets Annaler*, 1888 (*en passant*, I may mention that this periodical contains a vast store of knowledge, which is nearly totally unknown outside Sweden on account of the articles being written in Swedish). In principle this instrument is neither a constant volume nor a constant pressure thermometer. It determines ΔP, when the volume V_1 at the pressure P and temperature t is pressed into the volume V at the pressure P and the temperature T. The readings thus represent :—

$$\Delta P = \frac{V_1 P}{V(1 + KT)}[1 + \alpha(T - t)] ; \quad . \quad . \quad . \quad . \quad (1)$$

K is the cubic coefficient of expansion of the material of the pyrometer bulb. The way in which Wiborgh eliminates the necessity of knowing t and P is wonderfully ingenious. Referring to Fig. 3 we observe a bulb Q′ and a tube Q with a mark r. When the pyrometer is put *in situ* and the bulb has acquired the temperature T_1, you turn the screw s slowly till the mercury from the rubber reservoir reaches the mark r. It then stands on the zero corresponding to the particular value of P in the pressure gauge B_1. By turning the milled head O′ you find the particular scale required. Afterwards you turn the screw s till the mercury reaches the mark m, and you read off the temperature as with an ordinary thermometer. Anybody familiar with the theory of gases will see that this is theoretically quite correct. The fault of the instrument is that you must immediately after a reading bring the mercury back to the mark m'' as sudden cooling might suck mercury into the pyrometer bulb. This fault can be so easily overcome that one marvels that a man of Wiborgh's great skill overlooked it. You have simply to enclose a small valve in V″ which will float up on the mercury against a

heating at *m*. With this modification an instrument like this, carried out in fused quartz, would be a standard instrument of the greatest value to non-ferrous metal experts. Professor Wiborgh's description was remarkable for



its lack of lucidity, but all the same the instrument had a considerable vogue. I may add that the compensation bulb Q′ is an application of the well-known Petterson principle, and it was suggested by Otto Petterson himself,

Dr. E. Griffiths: The original Wiborgh pyrometer was described in the *Journal of the Iron and Steel Institute*, ii., p. 110, 1888. In later forms of the instrument the mercury manometer was replaced by a pressure gauge resembling an aneroid barometer.

The same objections apply to this pyrometer as to all gas thermometers hitherto developed for industrial use, namely, fragility, permeability of the bulb at high temperatures, and liability to leak.

Mr. H. S. Taylor: I was in Princeton at the time Dr. Northrup was starting his preliminary investigation on that furnace, and so far as I understand it, it is not a type of furnace useful for everyday operations, because the apparatus required is complicated, and the initial capital value would be considerable. I was not there sufficiently long to see the full development of the apparatus, and I am looking forward with interest to what Dr. Northrup has further to say with regard to it. All I can say is that he was very optimistic about it, and he was hoping to be able quite readily to melt platinum-iridium alloys. That had been put up to him as a problem by the Washington people. He had always got a considerable amount of platinum-iridium alloy filings, and he regarded it as a problem quite capable of solution. He was hoping to extend the temperature scale which he investigated very considerably, up to 2,000° C., and he was making investigations in that region, and was going to measure his temperatures with the aid of the tin pyrometer.

Dr. Walter Rosenhain, F.R.S.: I should like to express my very great interest in Dr. Northrup's paper. The development of this type of furnace, as far as I can judge from the paper, is a matter of the utmost interest and of very considerable promise. It is true that the electrical appliances required are of a somewhat elaborate nature, apparently a battery of condensors and various coils, but whether they would really militate against the possibilities of the furnace to the extent which the last speaker suggested, I think is doubtful, because, after all, the appliances required for the ordinary electric furnace either of the arc type or the carbon resistance type are by no means simple or cheap. Whether, therefore, the cost would be so large as to prohibit the use of the Northrup furnace I do not know, but I am inclined to doubt it. At all events the possibility of producing very high temperature in the total absence of carbon or any other resistor which is liable to destruction should counterbalance a great deal of the extra cost.

Taking the papers in order, with regard to the nickel carbides mentioned by Dr. Griffiths, the existence of the nickel carbide eutectic has been fairly well known to metallurgists for some time, although the fact that it is so convenient for a fixed point for pyrometric purposes is new and valuable. I would suggest the possibility of using another point of somewhat the same kind, also very well known and definite, viz. the iron carbide eutectic point formed when iron is melted in excess of carbon. This gives a temperature very near 1,130° C. This eutectic contains about 4·5 per cent. carbon. There are, however, some difficulties. There is an arrest-point at a somewhat lower temperature which occurs under certain conditions, but that may be avoided if the conditions are suitable.

With regard to Mr. Whipple's paper there is a difficulty which has occurred to me as perhaps rather more serious than Mr. Whipple would lead one to suppose, and that is the thermoelectric effect at the terminals where the wires leading down to the buried cold junction are connected to the wires leading either to the galvanometer or to the thermocouple. It is true that all these connections are intended to be connections made of identical metals, copper or brass, but when these metals are examined it will be found that a copper terminal with a brass binding screw and various solders are

also used. Provided that the temperatures of these various terminals are very nearly alike, this does not matter, because the thermal effects balance out, but I have certainly found it necessary where high accuracy is required to avoid any connections of this kind. If such connections are adopted in works trouble would be likely to arise, unless special precautions are taken, because they would always be in a fairly warm place, not far from a furnace, and the temperature changes rapidly from place to place in the vicinity of a furnace. If Peake's compensating leads are used that is a considerable advantage, but the difficulty does exist, although it may probably be overcome by careful arrangements. In some works Mr. Whipple's suggestion of using a buried cold junction is obviously a good idea, especially where the furnaces used are not very large and they are supported on stands away from the floor so that the ground around the furnace does not receive any very large amount of heat; but any metallurgist here knows what the vicinity of, say, an open-hearth steel furnace is like. Except in the special circumstances I have mentioned, 10 ft. is not nearly far enough away from such a powerful source of heat to allow of a constant temperature being obtained, 30 or 40 ft. in the horizontal direction would be necessary, whatever may be necessary vertically.

I am very much interested in the instruments Mr. Brown has described; I do not, however, agree with his statement that the ordinary potentiometer cannot be used in works practice. There are forms which are sufficiently portable; these have been in existence for years, and are used as portable instruments in works with very considerable success. I am a little interested to know the origin of what is really a vital feature of Mr. Brown's automatic controller, and that is the depressor bar. The action of the instrument depends entirely upon the introduction into it of the means of depressing the pointer and making it produce contact. I believe that was first used in the thread recorders of the Cambridge Scientific Instrument Company, and if that is so it should be stated, because it is a vital factor in Mr. Brown's instrument. It is a very ingenious and interesting method, and the priority of it should be referred to.

Mr. C. E. Foster: I am very much interested in Dr. Griffiths' remarks about the size of the hot body wanted for standardizing a radiation pyrometer. I have very great sympathy with his difficulties in producing in the laboratory conditions that can be obtained in the works, but I do not think that these difficulties exist to any great extent under industrial conditions. There is plenty of hot body so far as the comfort of the user is concerned, perhaps more than is required, but it is a factor that has to be considered from the standardization point of view. Then with regard to Mr. Whipple's suggestion to bury the cold-junction, that is a very good method, as I know by experience, and as Dr. Rosenhain has mentioned suitable for small furnaces, but as far as applying it to large furnaces is concerned, it is very much more difficult. I believe it can be used under certain selected conditions, but if the method is to be applied to a very large furnace you must decide that either your distance from the furnace must be very big or you must bury the method instead of the junction.

With regard to the point raised by Dr. Rosenhain about the depression of the recorder pointer, I think I can re-assure him on that point. It is as old as 1889 when it was proposed and patented by Drake and Gorham, and for an electrical instrument that is quite a long time.

Referring to the paper by Mr. R. P. Brown, the automatic control of a furnace by means of a pyrometer is very fascinating indeed. It has all sorts of difficulties in it, but I think it is a coming development. In 1908 I

designed an installation of recording pyrometers, including a system of controlling automatically the electric furnaces to which the pyrometers were applied. My recent acquaintance with it was in 1912 when I was asked to make such an instrument, and the suggestion was made as a preliminary step that we should control by means of a system of lamps, like Mr. Brown's, a green for too low, a white for all right, and a red for too high. The system was described to me by an English manufacturer as one he had seen in the States. I had not been long back from the States and I was a little annoyed with myself that I had no knowledge of it. I inquired into the matter, however, and found out, subsequently, to use an American expression, that there was a "nigger in the wood pile," and that in the case to which my attention had been drawn, an operator was reading the temperatures and was working the lamps.

The Chairman : The best form of automatic control.

Mr. Foster : Perhaps this is so. The experience of this particular case was that it was better to let the man see the recorder and the records he is making, and that then he got better indications of what to do with his furnace than by flashing lamps.

I have made a considerable study of this matter of automatic furnace control in conjunction with pyrometers. It is my experience that when the matter is considered in detail it is found that the advantages of such automatic control are often more apparent than real in industrial heating processes. Great advances have been made by furnace builders and furnace users with the result that heating processes are now very considerably standardized. There is, nevertheless, even to this date some amount of experimenting to be done, the heating processes are not yet reduced to an absolute matter of routine, therefore the attention and presence of a fairly skilled furnace man is necessary. Given a reasonably accurate recording pyrometer a furnace man can carry out intelligently and accurately any given heating programme. With the present development of pyrometry and furnace building, the installation of automatic control frequently tends, instead of reducing the supervision necessary, to transfer that supervision from the furnace to the apparatus controlling the furnace. It is a fairly safe prediction that automatic pyrometric control will become more common in the future, but I regard such development as being ahead of the immediate needs of industrial heating processes.

Mr. S. N. Brayshaw : I should like to say a word about standardizing pyrometers, and if it sounds commonplace my excuse is that it is a description of rough workshop method which our own workman can use and from which he can get good results. Some 12 or 15 years ago, Mr. Whipple supplied me with a copper-tin alloy : I think it was Cu_4Sn. It is a eutectic alloy which has a sharp freezing-point at 738° C., and we sent it to the National Physical Laboratory to be tested. We used it after that quite frequently, and then sent it again to the N.P.L., and I have a letter from the Director saying that they were not able to find any difference in the freezing-point on the two occasions, and that their tests showed that it was a good standard. We had a deep graphite crucible made so that we could get a good depth of immersion with an ordinary pyrometer stem about $\frac{7}{8}$ in. diameter. We simply covered the top of the crucible with an asbestos sheet and made a hole for the pyrometer tube which fitted tightly into it. There was another hole for a gas tube through which gas flows continually into the upper part of the crucible, and a third hole which was left open. From this third hole the gas escapes and is lit, so that a flame plays over the hole from beginning to end of the operation. The alloy is covered with charcoal and raised to 750° or 760° C.

In this way you have an atmosphere of coal gas which can be depended upon. The charcoal at a temperature of 760° C. does not glow at all, and at the end of the experiment comes out quite black without any formation of ash at all. A workman can be taught to use a simple arrangement like this, and it is on a big enough scale to dispense with accurate manipulation. The alloy takes a long time to freeze. You see the curve coming down quickly and then it halts at 738° C. for perhaps a quarter of an hour before it plunges down again. We have used that alloy to standardize our instruments to about one or two degrees.

It so happens that a commercial carbon tool steel that can be bought by the ton, or the hundred tons, containing 1·1 to 1·2 per cent. carbon, and about 0·5 per cent. of tungsten, also has the point Ac 1, 2, 3 at 738° C., and that point is not moved appreciably by any ordinary variation of sulphur, phosphorus, silicon or manganese content. We have taken, I venture to say, thousands of standardizations from that steel which has the change point at 738° C.

I might just mention one more point on the subject of high temperatures, or what we call high temperatures. We call anything above 1,500° C. a high temperature, but our electrical friends do not think much of that. I have in my hand a photograph of the floor of a furnace which showed a temperature of 1,800° C. on one of the Cambridge Scientific Instrument Company's new optical pyrometers, which was standardized before the experiment and verified afterwards. This photograph shows some very good fire-brick that has dripped down and glazed some of the special refractories that we were trying. The temperature has to be taken through a good size hole in the furnace, and I want to ask Mr. Whipple if he would tell us what to do to avoid the dreadful loss of heat through the hole. We focus the instrument first of all and get everything right and then the furnace plug is taken out. I suppose the instrument takes 5 seconds before we have got the reading and by that time we find the temperature has run down seriously. Probably you can lose nearly 100 degrees in half a minute. The furnace in question is 1 ft. cube inside and the opening is 3 in. diameter. Of course you might have a fire-clay tube all the way from the furnace to the instrument, but if you retain the heat in this way you run the risk of getting the instrument too hot.

Mr. E. H. Rayner: From the electrical point of view, the suggestion of Dr. Northrup is a very fascinating one. It appears to me from the details that what is required is a large part of the plant and of a fairly high-power wireless telegraph installation such as for long distance telegraphy. It is a perfectly practical proposition; you could buy it "over the counter" in ordinary times. He seems however to have devised a satisfactory spark gap, which is one of the main difficulties.

Mr. Robert W. Paul: I take the opportunity presented by the presence of this large gathering to suggest that we avoid a looseness of expression which is creeping into pyrometry. One of the speakers referred to a milli-voltmeter as a pyrometer, and another to a thermocouple as a pyrometer. In business, this practice introduces risk of misunderstandings, except in the case of instruments which are self-contained. I think we should clearly decide that a thermoelectric pyrometer installation comprises an indicator (or recorder), leads and thermocouple; in some works the last is called a poker, with the result that there is a tendency to use it as such.

Mr. J. Drummond Paton: I wish to ask Mr. Griffiths a question. He refers to the iridium contaminated portion of the thermoelement and that raises a question which has interested me for a long time, viz. the permanency of the thermocouple. It appears to me to prove that the

metals of your selected couple must be as near to each other as possible on the "positive negative" scale to avoid this transference. The consequence also is that you must have very delicate instruments to indicate the thermoelectric effect on elements so slightly removed from one another. I have been interested in the stability of alloys, and I hold that this phenomena (which I have come across in other cases) in a way can be used to prove the stability of alloys. If I take a couple and submit it to heat, and by continued treatment with heat I get a transference from one element of the thermocouple to the other, it indicates the instability of the alloy at the thermal junction.

By subsequent transference of iridium (in Mr. Griffiths' case) we get a diminution of e.m.f., with a corresponding increment of stability in the alloy.

The inference is that the "Chatelier" effect will be a minimum at the point where transfusion or segregratiou is a minimum, and the maximum stability of any alloy at any temperature is defined by a minimum "Chatelier" effect under such conditions.

Mr. A. J. Webb: Mr. Whipple said that in the case of base metal junctions the wires could be carried in one length from the hot to the cold end. In the case of the rare metal thermocouple that is not possible. I should like to ask how he arranges to secure the uniformity of the temperatures of the junctions of the rare metals with copper leads, because that seems to me a possible difficulty, if you are using a high temperature, in order to make full use of the 10 ft. or 20 ft. of cold ground.

Dr. G. B. Bryan: I was wondering in connection with Dr. Northrup's furnace whether he had considered the use of the Poulsen arc in producing the oscillating current. I notice he uses the ordinary spark installation, and it may be possible that a good size arc would be more convenient as it gives a continuous oscillation.

Mr. R. S. Whipple: In reply to Mr. Webb's question, I omitted to state that if compensating leads are fitted to the pyrometer, the cold-junction is transferred from the rare metal couple to the ground or whatever spot you wish. There is, as Dr. Rosenhain points out, the difficulty of small thermal forces set up by the unequal heating of your pyrometer terminals. In one of the installations—of which I showed a photograph (Fig. 5)—the wires are taken directly from the pyrometer head itself to the buried junction without the interposition of any terminals. In many pyrometers a metal cap surrounds the terminals, and this tends to give uniformity of temperature to the two terminals, so that any error introduced from this cause is a small one. In the case of an accurate laboratory experiment the error is avoided by running the leads of the pyrometer itself to the cold-junction without the interposition of terminals.

Mr. Brayshaw remarked on the efficiency of the alloy he used for the standardization of pyrometers. This is a eutectic alloy (60/40 copper, tin) of the copper-tin series developed by Heycock and Neville. In practice the stability of the freezing-point of this alloy is remarkable, and I have known of cases where the melting-point has remained constant for many years.

The question Mr. Brayshaw put is a difficult one to answer. I have always urged furnace builders to make their furnace walls thicker, so that the radiation losses should be reduced to a minimum. I am afraid it is impossible to avoid some loss of heat when a plug is opened in the furnace. It should be possible to fit a glass or quartz window to the

furnace after certain precautions have been taken, and if the absorption power of the glass has been determined the temperatures could be obtained by means of an optical pyrometer.*

With regard to Mr. Brown's paper on control, I have been unable to understand why automatic control has not been adopted. In one large iron works the temperature of the hot air supplied to the blast furnace is maintained at a temperature of about 600° C. When the apparatus was ordered, the specification stated that the temperature must be kept constant within ± 10°, and that specification has been conformed to for some years. A resistance thermometer is fitted into the hot air main which is about 15 in. in diameter, and which is connected to two pipes, one through which cold air is admitted, and the other along which the hot air from the stove has passed. In the cold air supply a butterfly valve is fitted. At the commencement, when a new stove is switched on, the cold air valve is opened to its fullest extent and then gradually, as the hot air from the stove cools down, so the butterfly valve is automatically closed and the cold air supply shut off.

In another works a large soldering iron weighing about 36 lb. is maintained at a constant temperature by means of an automatic regulator controlling the gas supply to the iron. The regulator is electrically connected to a thermocouple placed in the iron and the regulation depends entirely on it and its necessary apparatus.

Another successful example of automatic temperature control is that fitted to the McLean spectroscope at the Cape of Good Hope. The spectroscope is mounted on a large telescope and is enclosed in an aluminium covered box. The box is heated by means of electric heaters controlled by a sensitive resistance thermometer and relays. In an experiment lasting over twelve months it was found that the temperature inside the prism box did not vary by more than $\frac{1}{100}$° C., although the air temperature from which the spectroscope was working varied by considerably more than 30° C. This control was designed by Mr. Horace Darwin; the details of a very similar one are fully explained in the paper read by him before the Physical Society.†

Dr. Rosenhain was very modest; he himself designed a potentiometer which may be easily taken round a works, and is at the same time an accurate scientific instrument.

Mr. W. Bowen (Leeds) (*communicated*): The papers read at the meeting are rich in information of a valuable nature, and one very important note that was struck is that pyrometer users are now taking pyrometers seriously into their works routine for manufacturing along the most scientific lines. I should consider that a periodical meeting of the members of a scientific institution such as the "Faraday Society"—say once or twice a year—for the purpose of discussing pyrometry and its applications would be an acceptable innovation.

I feel that the papers submitted at this particular meeting did not deal sufficiently with "pyrometers," and that too great a proportion of an evening intended to discuss this subject was devoted to one particular application, namely, the measurement of temperatures in the manufacture

* *Note added December 5th.*—In some cases it is advisable to insert a blind tube made of a highly refractory material into the furnace and to sight on the inside of this tube. In the case of any of the well-known radiation pyrometers, this is the most effective way of measuring the temperature of the furnace. The method suggested in the discussion can only be used when optical pyrometers are being employed.

† "An Electric Thermostat," by Horace Darwin, *Proc. Phys. Soc.*, xix. 64–72.

of steel. Descriptions of such applications are a most valuable addition to the present information of both users and makers of pyrometers; but there are so many points in regard to pyrometry itself which may be discussed.

For long years engineers fought against the introduction of the pyrometer into their works, the attitude being that "what was good enough for my father is good enough for me," and that "I can guess the right temperature closely enough by the eye." That day is happily gone, and has given place to the use of scientific instruments for the accurate determination and accurate reproduction of correct working temperatures. But may I suggest that there is a great tendency for the pendulum to swing over to the other extreme, namely, the anxiety of works engineers to read high temperatures to such a degree of accuracy that they are apt to lose sight of temperature variations which are almost inseparable from heating in bulk, and of other factors in heat-treatment which are of equally vital importance. As an example, I would mention that times out of number have I seen firemen of intelligence apply a magnifying lens to the usual pattern of works pyrometer indicator or recorder, so as to read a temperature of, say, 800° C. to within one degree. Apparently it never strikes them that variations in temperature in various parts of the furnace are as great as 3–5 per cent. under perhaps the best conditions of firing in a medium-sized furnace; they do not take into consideration that the cold-junction temperature of a thermocouple may easily be 10° different from the setting of the indicator; and they have forgotten—if they ever took the trouble to read—the instructions of the pyrometer manufacturer. Moreover, my remarks are not confined merely to the works foreman, but to the metallurgical chemist who "strains after gnats" of one or two degrees in the high temperature regions, and "swallows camels" in the uneven heating of the materials which are under treatment, in his selection of the wrong type of pyrometer for his work, and in the improper application of his pyrometer to attain the best results. If the meeting results in making these facts patent to pyrometer users, it will have served a good purpose indeed.

A few of the papers read before the meeting have implied that there is room for the pyrometer makers to improve their instruments by providing greater accuracy in the region of very high temperatures. This is undoubtedly true; their efforts in this direction are unceasing, and with the collaboration of the now numerous pyrometer experts who apply these instruments in actual practice, rapid strides are confidently expected in their perfection.

Referring to Dr. Northrup's description of his "pyrovolter," and the similar instrument described by Mr. Brown, this is an interesting development of the potentiometer method adapted for works practice. However, it possesses the disadvantage of incorporating a battery, which the works engineer usually tries to avoid if possible, and also the necessity of a periodical adjustment of the indicator by hand, which the average furnace operator cannot be relied upon correctly to make. Dr. Northrup and Mr. Brown both claim that their instruments are designed to eliminate errors in reading due to temperature variations along the immersed stem, the connecting cable, and in the indicator. Mr. Brown also mentions that he now constructs an indicator of about 1,000 ohms, presumably the resistance of the total circuit. Now, since the argument in favour of a thermocouple pyrometer having a high-resistance circuit is that variations in temperature along these parts produce a negligible effect on the temper-

ature readings, it appears to me that Mr. Brown, in adopting the "pyrovolter" principle, is striving to eliminate an error which is already negligible in his simple outfit; in other words, a somewhat wasted effort as regards workshop application.

Actually, in a pyrometer having a total circuit resistance of about 1,000 ohms, having the usual proportion of manganin and copper resistance in the circuit, I should not expect to find an error of more than two or three degrees in the temperature readings under somewhat extreme fluctuations of the room temperature; this error is almost unreadable in the usual works indicator, of range up to 1,000° C. or over, with scale calibrated at 10 or 20° intervals. Moreover, there are other sources of possible error of equal or even greater magnitude, such as the pivot friction of the moving coil, the zero-creep of the control spring, cold-junction effects, etc.

I heartily congratulate Mr. Brown on his production of the high-resistance movement of which he writes; it is a remarkable achievement. At the same time, it is not necessarily a "high-resistance" that is aimed for in a pyrometer, but a "high-sensitivity" movement, and that apparently Mr. Brown has produced. It may be worth while mentioning here that the manufacturer of the rare-metal thermocouple pyrometer adopts perforce the high-sensitivity movement, on account of the small thermo-e.m.f. available from the thermocouple, and also due to the high co-efficient of resistance of platinum and its alloys with temperature which necessitates a high resistance. His movement is thus one of low torque with its consequent danger from "zero-creep" and lack of robustness. On the other hand, the maker of base-metal pyrometers has very much larger forces at his disposal, and in consequence may adopt the same course, namely the use of a movement of low torque and very much higher resistance than that of the rare-metal pyrometer circuit; or alternatively, he may advocate a low-resistance circuit with consequent high torque, and present to the pyrometer user an instrument of much greater robustness, and one almost—if not entirely—free from "zero-creep."

Professor F. G. Donnan, F.R.S.: With regard to Mr. Brown's instruments, there is nothing very new in the principle. We have all used it for electrically controlled and heated thermostats for many years, and I would mention, in connection with the shunted portion of the current switched in and out, that I find it very convenient using carbon contacts with a choking coil and condenser in parallel to choke out the arc.

Mr. E. F. Northrup (*communicated reply*): I have been trying to find time to write relative to the discussion of my paper presented before the Society, but I am really too busy to do so. I can only remark that, in spite of war conditions, the development of the Northrup-Ajax high-frequency induction furnace has been pushed vigorously, and a test, quite successful, has already been made on a 60-kw. furnace. In due course the theory and full description of this new method of heating will be given to the public.*

Mr. Richard P. Brown (*communicated reply*): Dr. W. Rosenhain refers to the use of a depressor bar in my automatic control pyrometer. As Mr. C. E. Foster states, this is an exceedingly old construction and is discussed in U.S. patents of Brewster in 1887.

Mr. W. Bowen comments on the fact that the Brown Instrument Company constructs an indicator of about 1,000 ohms. I quite agree with Mr. Bowen that the new form of heat meter with some similar features to Dr. Northrup's pyrovolter is almost unnecessary. It is, however, quite true that we carried

* Some illustrations have since been received (see Figs 2 and 3, p. 12).

on development work in producing the heat meter before we were able to produce a milli-voltmeter of this exceptionally high resistance. I think the demand for the heat meter is therefore eliminated.

The milli-voltmeter which we produce for temperature measurement to-day, using an aluminium coil, has usually a resistance of 30 ohms per milli-volt. The platinum rhodium thermocouple produces approximately 20 milli-volts for 3,000° F. or 1,600° C., for which the scale is usually calibrated. Such an instrument has therefore 600 ohms resistance.

With a thermocouple formed of nickel chromium for high temperature service we secure 40 milli-volts for a range of 2,000° F. or 1,100° C., and such an instrument has 1,200 ohms resistance. We use also a thermocouple formed of nickel chromium and constantin which produces approximately 60 milli-volts at 1,600° F. or 870° C. Such an instrument ordinarily has a resistance of 1,800 ohms. The instrument is a double pivoted one of high sensitiveness, as Mr. Bowen states.

We overcome the zero creep by using special springs of exceptionally high grade, which can be procured from only one manufacturer in this country. These springs are of exactly the same thickness and length, and are put on the moving element opposing each other. We build ammeters of approximately 5 ohms resistance, also low-resistance pyrometers, but from my experience I would state that we have perceptibly no more zero creep in the exceedingly high resistance instruments than in instruments of 5 ohms resistance.

This portion of the discussion concluded the business of the afternoon session, and the meeting adjourned at 7 p.m.

PYROMETRY APPLIED TO THE HARDENING OF HIGH-SPEED STEELS.

The first part of the evening session, which resumed at 8.30 p.m., was devoted to the consideration of a group of papers and communications dealing with the application of pyrometry to metallurgy, and particularly the metallurgy of steel.

Professor J. O. Arnold, F.R.S. (University of Sheffield), spoke on "Pyrometry Applied to the Hardening of High-speed Steels."

The subject I have to speak about is the hardening of high-speed steel. I hope you have formed no hopes that I am going to enter into a discussion of high-speed steel. It is a very ticklish subject. I have only tried it once in London, and it was more than my life was worth. At the same time, one can deal with advantage with the hardening, pyrometrically controlled, of high-speed steel. It is a matter of general knowledge that steel metallurgists have come almost unanimously to the conclusion that the most usual and the best average temperature to harden high-speed steel is 1,300° C., and I want to lay before you to-night some of the actual results we have obtained at Sheffield University on this basis.

In my opinion there is nothing that secures regularity of temperature so efficiently for this purpose as the salt bath. All high-speed steels are generally hardened through a bath of barium chloride, melted by two iron electrodes to a state of fluidity, and by adjustment the current is kept to a point which enables a temperature of 1,300° to be maintained, or very nearly so. The tools to be hardened are immersed in this bath, and then they are quenched in various ways—in air, in an air blast, in oil, and in water. We have made several researches on this matter at the University which have not hitherto been published, and some of the data which I am at liberty to publish I think may prove interesting.

First of all, I will explain a simultaneous set of experiments taken with five different pyrometers. The pyrometers we have used are, first, the Féry. This is a thermoelectric pyrometer, in which the heat-rays are focused on to a small thermocouple which gives a high e.m.f. over a small increase in temperature. This is measured in terms of current by means of a D'Arsonval galvanometer. The galvanometer registers temperatures from 900° to 2,000° C. Readings are taken with one-fifth of full aperture of the telescope opening. It is essential that the galvanometer be kept at a low constant temperature.

The second type of pyrometer is also a Féry, but is a less delicate instrument with a spiral spring. The heat-rays are focused on to a small bimetallic spiral, the movements of which under the influence of heat are greatly magnified by means of a light aluminium pointer. This pointer moves over an arc graduated in degrees of temperature up to 1,700° C. In use, these

instruments should be allowed to attain "room temperature," the indicator then being set at zero. After opening the aperture, the first stop of the indicator is the desired temperature reading, as the temperature of the surrounding atmosphere will in a short time give an increased reading.

The third type we used, the Foster base-metal thermocouple, is of course more or less based on the Le Chatelier pyrometer, in connection with which, by the way, we ought to recognize Professor Tait as the pioneer of this type. The working temperature of this pyrometer is a maximum of 1,350° C. The couple is nickel-chrome alloy against nickel or against a different nickel-chrome alloy. The e.m.f. generated at a given temperature is, however, much greater than is the case with the platinum series of couples, so that a much more robust galvanometer of the low-resistance type may be used. The stem of the couple, except the twisted end, is protected by a refractory covering, and provided that only the twisted end is heated to the temperature to be measured, very reliable readings may be obtained. The mass of the couple is comparatively large, and should that portion from the couple to the leads be heated, there ma be low readings due to loss of heat by conduction. The galvanometer is furnished with a ready means of adjusting to room temperature, so that no corrections for cold-junction effect are necessary. Temperatures for reliable readings are from 500° to 1,400° C.

The fourth type of pyrometer was the Leskole optical or modified Wanner. In this, by means of an optical system enclosed in a telescope, light rays of different wave-length are selected from the source whose temperature is to be measured, and also from a standard electric lamp illuminated by means of a 4-volt accumulator. It is so arranged that light from the source and that from the standard are polarized in planes at right angles to each other, so that on rotating the analyser it is possible to enhance the brightness of one-half the field and diminish that of the other, and so bring each half field to an exact match in red tint. The position of the analyser, as indicated by a pointer, gives on reference to a table the desired temperature. Periodically the electric lamp is checked against an amyl acetate flame of definite dimensions.

The fifth type was the Mesuré and Nouel, for which I have a very great affection. Its one fault is that the results depend so very largely upon the personal equation. If you can obtain an observer who has got into the way of making accurate results, properly used I regard that as one of the most accurate pyrometers we have. In it, the light rays from the heated body are plane polarized by passing first through a Nicol prism, then a quartz plate of definite thickness, and finally a Nicol prism which acts as analyser. The quartz plate rotates the plane of polarization of each coloured ray to an amount depending on its wave-length and at the same time absorbs the yellow rays. On rotating the analyser the colour seen passes at once from red to green, and between these is the sensitive tint, the position of which indicates the temperature by means of angle of rotation, which is then referred to a table.

Our system in this research is this: we select our best senior undergraduates. Each man has a different instrument, and the readings are taken simultaneously from the barium chloride bath, neither man having any idea of what the other is getting, and I was very much astonished to find the splendid results we got from all these pyrometers. It at once occurred to my mind that, properly used, whatever type of pyrometer was employed was reliable, and a great debt by metallurgists is due to the physicists to whom these instruments are due. Where bad results have been obtained,

TABLE I.

Temperature Measurements of the Electrically Heated Barium Chloride Bath used at Sheffield University for Hardening High-speed Steels.

January 28, 1914.	Names and Types of Pyrometers.					Mean Temperatures. Degrees Centigrade.	Remarks.
	Féry Radiation.	Féry Spiral.	Foster Immersed Thermo-couple.	Leskole Optical (Modified Wanner).	Mesuré Optical.		
Hr. Min.							
11 43 a.m.	Not taken	1,290	1,285	1,320	1,300	1,299	
11 56 a.m.	1,310	1,290	1,300	1,270	1,300	1,294	Each set of temperatures taken simultaneously
12 7 p.m.	1,310	1,280	1,310	1,270	1,310	1,296	
12 23 p.m.	1,300	1,280	1,290	1,300	1,300	1,294	Grand mean 1,296° C. *

* 2,365° Fahrenheit.

I think it is very largely due to lack of skill of the operator. We were aiming at a mean temperature for hardening of 1,300° C. before quenching. The grand mean of this large series is 1,296° C., which is a pretty good result (see Table I). If you go through all the figures you will find that the differences in every case are such as might be due to slight variations in the instrument, but more, I think, to the personal equation and the observer. I may say that I know what is coming up later—that hardening high-speed steel with the barium chloride bath secures black-body conditions throughout, and that may have something to do with the remarkable agreement of all the results with five different pyrometers. The Féry spiral does not pretend to be anything more than a rapid rough approximation. So much for the first table. In the second table, we have

TABLE II.

June 16, 1914.	Names and Types of Pyrometers.			Mean Temperatures. Degrees Centigrade.	Remarks.
	Mesuré Optical.	Leskole Optical.	Foster Immersed Thermo-couple.		
Hr. Min.					
10 40 a.m.	1,310	1,220	1,310	1,280	
10 45 a.m.	1,300	1,300	1,300	1,300	
10 55 a.m.	1,300	1,230	1,280	1,270	
11 5 a.m.	1,280	1,246	1,270	1,264	
11 15 a.m.	1,300	1,280	1,300	1,294	
11 23 a.m.	1,300	1,295	1,300	1,298	
11 36 a.m.	1,300	1,290	1,310	1,300	Grand mean
11 40 a.m.	1,330	1,320	1,330	1,327	
11 44 a.m.	1,325	Not taken	1,310	1,317	
11 46 a.m.	1,310	ditto	*Couple broken*	1,310	1,305° C. or 2,381° F.
11 55 a.m.	1,300	ditto	ditto	1,300	
12 4 p.m.	1,300	1,300	1,320	1,307	
12 12 p.m.	1,300	1,310	1,330	1,313	
12 19 p.m.	Not taken	Not taken	Not taken	—	

three photometers, but with a large number of observations, and here we get bigger variations. As you will see, the grand mean is 1,305, and we were aiming at 1,300. I have a great faith in observations like these in taking the grand mean. There again you will see, taken as a whole, the Mesuré and Nouel gives a very good constant, but the variations in this set of observations are considerably greater than in the first series, showing the influence of the personal equation. So much for high-speed steel.

At the present time, I am sure my friend Mr. Cosmo Johns will admit that it is very important that we should get a constant record of the temperature of steel tapped from the open-hearth furnace, and that is a very difficult matter, particularly in a large furnace. Therefore, I thought it might be well to include a few results obtained from our small 2-ton Siemens furnace in the Sheffield University. One is particularly interesting. The first series are temperatures taken in 1910 with the old original Wanner. In putting

in a Siemens furnace, it is usual to charge it with what is called a pig melt, to consolidate the bottom after repairing it, when you are starting from cold; and this in our small furnace has reference to a pig melt of hematite iron of only half a ton, which we melted to a bright heat and cast into a ladle, and then allowed to cool somewhat, because we were going to utilize this melt to make iron for casting floor-plates for the furnace. I got some good students, and we cast five plates weighing 1½ cwt. each, and we took very carefully the casting temperature of each plate. It was in a small ladle, and it was a small charge even for a small ladle, so radiation would be pretty rapid. The casting temperature of the first plate was registered at 1,300° C.; the second was 1,280, the third 1,243, the fourth 1,258, and the fifth 1,208. That means that the average fall of temperature during the casting operation per plate was 18° C.

I have also selected a series of experiments carried out at a later date, in which two undergraduates were working with a Leskolc and a Mesuré and Nouel pyrometer. The mean of their readings was taken and put down on the board. That was in December, 1914, and the casting temperatures of the pig melt were very high, 1,525° C. Of course, that is quite possible, but I rather doubt that reading; it was recorded as the mean of the two pyrometers. We cast five heats of structural steel, mean carbon about 0·35. The tapping temperature of the first heat was 1,600, the second 1,550, the third 1,630, the fourth 1,570, and the fifth 1,620. In our next run, in March, 1915, the pig melt casting temperature registered was 1,440, which I think is pretty near the average mark, and the heats were 1,625, 1,600, 1,600, 1,600, 1,590, and 1,600. I think the evenness of some of these results is too good to be true literally, but still I do not think they are very far off.

These are a few of the records taken at random from our long experience with the use of pyrometers in hardening high-speed steel and casting, and I hope they will form the basis for a valuable discussion.

OPTICAL PYROMETRY IN NON-FERROUS METALLURGY.

Professor F. G. Donnan, M.A., Ph.D., F.R.S., spoke on "Optical Pyrometry in Non-ferrous Metallurgy."

When using optical pyrometers in cases where the conditions for full (so-called " black-body ") radiation are not satisfied, as, for example, when observing open baths or streams of molten metal, it is necessary to apply corrections depending on the optical properties of the material examined. For any given spectral region employed, the correction depends on the ratio of the luminous energy radiated by the material in question to the luminous energy emitted by a full radiator in the same spectral region at the same temperature. In many cases the failure to make the necessary correction will result in serious errors, so that it is necessary to draw the attention of practical metallurgists to this matter. Mr. Cosmo Johns is going, I understand, to speak about the corrections necessary in the case of steel, whilst in the present note it is my intention to refer to the cases of gold and copper, two metals whose optical properties at high temperatures depart very widely from those of the ideal full radiator. A bath of molten copper shines with a beautiful greenish-blue light, a bath of molten gold with a bluish-green light. A short consideration suffices to show that this must be the case. Consider the case of copper, for example. Cold copper selectively reflects red light. Imagine a mass of molten copper, at a temperature, say, of 1,200°, inside an enclosed furnace at the same temperature. The total light coming from the copper will then correspond to full radiation at 1,200°. But as the copper selectively reflects in the red part of the spectrum, it must obviously be selectively emitting in the blue and green. Thus a mass of molten copper, deprived of this reflected radiation, will shine with a greenish-blue light. This conclusion depends on the assumption that the selective reflection in the red does not disappear with rise of temperature, an assumption which is justified by the experimental observations.

The emission-spectra of copper, gold, and silver at temperatures in the neighbourhood of their melting-points have been compared with the emission-spectrum of the full radiator at corresponding temperatures by Drs. Stubbs and Prideaux, working under my direction at Liverpool University.*

* " A Spectro-photometric Comparison of the Emissivity of Solid and Liquid Gold at High Temperatures with that of a Full Radiator," C. M. Stubbs and E. B. R. Prideaux (*Proc. Roy. Soc.*, A, 87, p. 451, 1912): " A Spectro-photometric Comparison of the Emissivity of Solid and Liquid Copper and of Liquid Silver

The following results are quoted from these measurements, which were made by means of a spectro-photometer of the König-Wanner type, as modified by Nernst and manufactured by Schmidt and Haensch. For details of the method and results reference must be made to the original papers.

Fig. 1 shows the relative emissivities of solid and liquid gold (i.e. relative to the full radiator at the same temperature) as dependent on the wave-length of the radiated light.

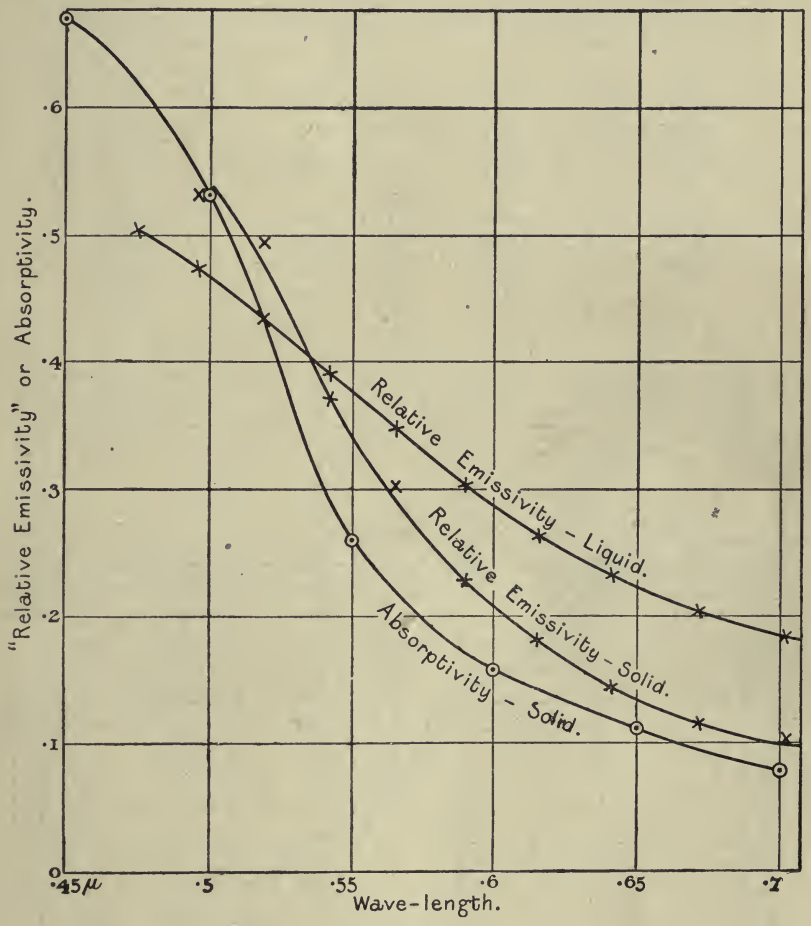


FIG. 1.

(Reproduced from the *Proceedings of the Royal Society*, by kind permission.)

In the next figure (Fig. 2) are shown the corresponding curves for copper and silver.* Thus, whilst the relative emissivity of molten copper is about 0·45 at wave-length 450 $\mu\mu$, it falls to about 0·12 at wave-length 700 $\mu\mu$.

at High Temperatures with that of a Full Radiator," C. M. Stubbs (*Proc. Roy. Soc.*, A, 88, p. 195, 1913).

* Curve I. Absorptivity, solid copper ; II. Relative emissivity, solid copper ; III. Relative emissivity, liquid copper ; IV. Relative emissivity, liquid silver.

The following table gives the black-body temperatures in degrees Centigrade of copper and silver at their melting-points, i.e. the temperatures of a full radiator giving the same emission of radiation.

Wave-length in $\mu\mu$.	Copper, M.Pt. 1,083·4°.		Silver, M.Pt., 960·7°.
	Solid.	Liquid.	Liquid.
700	896	917	792
675	912	928	799
650	924	942	804
625	943	956	808
600	966	973	816
575	988	989	823
550	1,007	1,003	831
525	1,018	1,015	838
500	1,028	1,026	845
475	—	1,033	—

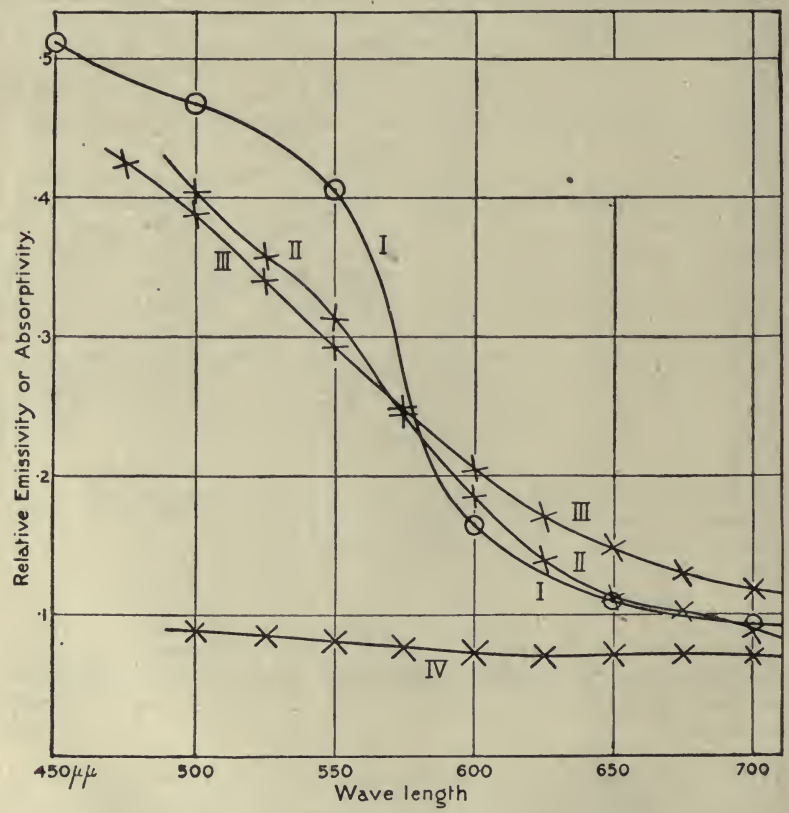


FIG. 2.

(Reproduced from the *Proceedings of the Royal Society*, by kind permission.)

Thus, an observer employing an optical pyrometer adjusted to give correct values for conditions of full radiation (as is always the case), and making use of a portion of the spectrum whose optical "centre of gravity" was, say, 600 $\mu\mu$, would estimate the temperature of molten copper in an open bath at its melting-point 110° C. too low. It may be remarked that this table of corrections can be used also at temperatures considerably different from the melting-point, since, so long as there is no change of state of aggregation, the optical properties do not appear to vary much with the temperature.

The following table gives the black-body temperatures for gold at its melting-point, 1,063·2° C.

Wave-length in $\mu\mu$.	Solid Gold.	Liquid Gold.
701·4	891·5	931
671·2	905	943
640·9	925·5	956·5
614·9	942	969
589·5	964	982
564·9	984·5	993
541·8	1,000	1,003
518·6	1,019·5	1,012
496·1	1,025·5	1,019
475·0	—	1,024·5

Thus, using an optical pyrometer giving black-body temperatures and employing a spectral region of mean wave-length 614·9 $\mu\mu$, an observer sighting on an open bath of molten gold at its melting-point would estimate the temperature about 94° C. too low.

It may be remarked in conclusion that optical pyrometers depending on polarizing devices for measurement purposes must be set at right angles to the surfaces of baths of molten metal, in order to avoid errors due to the polarization of obliquely radiated light.

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THE DETERMINATION OF THE TEMPERATURE OF LIQUID STEEL UNDER INDUSTRIAL CONDITIONS.

Mr. Cosmo Johns, F.G.S., M.I.Mech.E., read a paper on "The Determination of the Temperature of Liquid Steel under Industrial Conditions."

Introduction.

It is a common experience, that there is a marked thermal effect when liquid steel, flowing from the taphole of an acid open-hearth furnace, is succeeded by the first flush of slag which must have been at, approximately, the same temperature as the liquid metal. Viewed through blue glass the slag is much brighter than the steel. The differences are not merely perceptible: they are considerable, and, as is well known, are due to the differences in emissivity of substances in different states and of various substances in the same state. If an observer is correctly placed, and watches a stream of liquid steel, reflections of light from the sun or an arc lamp can be seen, and it becomes evident that the surface of liquid steel possesses in a considerable degree the property of reflecting light. The liquid slag is less efficient in this respect. Now good reflectors are poor radiators, and the optical effect described confirms the thermal effect noticed with liquid steel and its slag. The thermal effects described may be studied by means of the Féry radiation pyrometer, but its use has not been found practicable for determining the temperature of liquid steel in practice owing to the large corrections that must be made and the marked variations in readings that occur when different parts of the same stream are in the field. In the present writer's experience optical pyrometers using monochromatic light have proved most useful. Dr. Burgess * has recently published a most valuable account of investigations made in several American steel works, as a result of which he was convinced that the results obtained were of a sufficient degree of accuracy to justify the adoption of similar methods in steel works practice. The best confirmation of this conclusion is that the use of pyrometers to record the temperature of liquid steel and slags has been a part of the regular practice of one British works for nearly four years, after preliminary experimental work, which occupied some time, while no doubt similar methods of control have been used in other places in this country.

* Technologic Paper, No. 91, Bureau of Standards, Washington, 1917.

Sources of Error and Accuracy Attained.

The use of measuring instruments, where a certain degree of accuracy is required, in industrial practice calls for special precautions, otherwise their introduction might cause greater difficulties and variations than the methods they were intended to supersede. Apart from such precautions as are necessary for the correct use of the instrument under laboratory as well as works conditions, the optical pyrometer using monochromatic light gives very consistent results, provided that certain conditions are observed. The liquid metal is best observed from a short distance, say not exceeding 12 ft., and at an angle as nearly constant as possible, for observations where the results are to be compared. Smoke and fumes absorb so much light that differences of as much as 40° have been obtained between the windward and leeward side of the same stream ; observations should therefore always be made from the clear side. There are slight, and not always constant, differences in the light emitted from various parts of the same stream ; experience suggests that a field located in the centre of the side of the stream exposed to the observer gives the most consistent results on the whole. Reflected rays from extraneous sources of light must be rigorously excluded from the field.

It was found that a skilled observer could, with the aid of blue glass, from observations of the steel as it poured from the furnace into the ladle, estimate differences of possibly 10° and certainly 15° apparent temperature ; while men watching the pouring of the steel from the ladle into the moulds, where the increased viscosity, due to decreased temperature, and other factors gave greater precision to the estimate, could certainly distinguish differences of 10° apparent temperature. Any pyrometer adopted must therefore be capable of giving consistent readings with greater precision than 10°. As a matter of fact, a trained observer can, with a suitable instrument, obtain readings with a variation of 2·5°± under very favourable conditions,* and this degree of accuracy is more than sufficient for effective control of the metallurgical processes employed. For each class of steel it is only necessary to determine—for the particular casting method employed—the " normal " temperature, when the steel is tapped from the furnace, which gives the best result. This " normal " may vary as the process employed is modified. The measurements involved are, therefore, divergences from the particular " normal " adopted at the time, and as the range of variations in regular practice is small no appreciable error is introduced by considering the *differences* in the pyrometer readings as temperature differences.

Temperature Distribution in the Furnace Hearth.

In view of the life of the refractory materials employed, and of the fact that a layer of slag, composed of R.O. silicates, of some inches in thickness, intervenes between the bath of liquid steel and the flame employed for heating, the temperature distribution † inside the hearth is of some interest. As all the heat received by the steel must pass through the covering layer of slag the surface of the bath must be at a much higher temperature than the steel itself, and the higher that surface

* This is of course exceptional, but with the best type of instrument readings can be reproduced with a variation of 3°± whenever the conditions are suitable. The routine readings can be repeated with a variation of something less than 5°±.

† See postscript.

TABLE I.

Emissivity.	Position.	Pyrometer Readings with Temperatures corrected for Emissivity. $\lambda = 0{\cdot}70\ \mu$.							
			Beginning of week.				Later in same week.		
$e = 0{\cdot}56$	Centre of hearth..	Apparent temp. ..	1,600	1,590	1,615	1,620	1,625	1,615	1,610	1,625
		Corrected temp. C.	1,704	1,693	1,721	1,727	1,723	1,721	1,715	1,732
	Centre of roof ..	Apparent temp. ..	1,585	1,600	1,590	1,600	1,590	1,575	1,560	1,575
		Corrected temp. C.	1,687	1,704	1,693	1,704	1,694	1,676	1,660	1,676
	Tapping side wall	Apparent temp. ..	1,625	1,625	1,650	1,635	1,660	1,650	1,640	1,660
		Corrected temp. C.	1,732	1,732	1,760	1,743	1,771	1,760	1,749	1,771
	Port block where gas last entered	Apparent temp. ..	1,645	1,640	1,655	1,650	1,665	1,655	1,650	1,670
		Corrected temp. C.	1,755	1,749	1,766	1,760	1,777	1,766	1,760	1,783
	Exit port block ..	Apparent temp. ..	1,635	1,635	1,640	1,650	1,625	1,640	1,630	1,645
		Corrected temp. C.	1,743	1,743	1,749	1,760	1,732	1,749	1,738	1,755
$e = 50$	Surface of bath before tapping..	Apparent temp. ..	1,625	1,595	1,635	1,645	1,660	1,635	1,640	1,665
		Corrected temp. C.	1,754	1,719	1,766	1,777	1,794	1,766	1,771	1,800

temperature the more rapidly will the metallurgical operations be conducted. On the other hand, the properties of the refractory materials employed impose a temperature limit which cannot be exceeded without endangering the stability of the furnace structure. The readings tabulated below were taken immediately after tapping, with the gas shut off for the furnace walls, and just before tapping, with the gas momentarily shut off, for the surface of the bath.

In order to correct the observed readings and convert them into degrees Centigrade it is necessary to assume a value for the emissivity of the interior of the walls of the furnace and for the surface of the slag. The difficulty is less in the case of the slag than might be anticipated, for in the acid process it is invariably covered—at the time the steel is ready for tapping—by a peroxidized layer. Burgess assumed 0·53 for liquid oxide of iron; in this paper an emissivity of 0·50 is assumed for the slag surface. The slag below this peroxidized layer, which is what is observed flowing from the taphole after tapping, possesses its own emissivity, which can be determined with some degree of accuracy by comparing the apparent temperature of the last steel observed to leave the taphole and that of the first slag to appear. These must have formed contiguous layers in the furnace and be nearly at the same temperature. The assumption of an emissivity of 0·40 for the liquid steel enables that of the slag to be calculated. As will be pointed out later, there is an appreciable temperature gradient in both steel and slag when in the furnace, and a comparison of the mean temperatures might import a considerable error. Seasoned silica bricks, which form the surface of the interior of the hearth, contain a considerable quantity of magnetic oxide of iron,* and the face of the brick may be regarded as saturated with the molten oxide, with cristobalite grains projecting through the oxide. Its emissivity is therefore a doubtful value; an assumption that it is less than the molten oxide itself, though probably involving an error, can be corrected when a better value has been experimentally † determined. It is noteworthy that a very pure silica sand, 99·45 SiO_2, can occasionally be melted on the surface of the bath into a viscous mass of fused silica, that wraps itself round the tool employed to withdraw it from the furnace. It is not often that the temperature necessary to accomplish this can be achieved. It is very probable that a temperature nearer 1,850° C. than 1,800° C. is necessary.

Temperature Gradient in the Bath.

From Table I an average temperature for the surface of the bath may be assumed as 1,635° apparent = 1,766° C., in which case an assumption of 1,470° apparent = 1,615° C. for the average temperature of the steel would be in accordance with experience. This indicates a pronounced temperature gradient in the bath, as might be anticipated from the mode of heating employed. The character of the gradient can be determined by observations, at short intervals, of the stream first of steel and then of slag as it issues from the taphole into the launder. After the first flush of steel has passed, and the smoke cleared away,

* Cf. TRANSACTIONS of the FARADAY SOCIETY, vol. xii., March, 1917, p. 82.

† When a patch of new silica bricks, in a "seasoned" wall, is compared with the adjoining old bricks a marked difference in apparent temperature of about 20° can be observed. If the emissivity of new silica bricks at about 1,650° C. could be determined under oxidizing conditions the other emissivities could be calculated.

it is found that a sharp rise takes place between the first two observations, and that the rise is more gradual afterwards until the first streaks of slag appear, when another sharp rise occurs. With a bath 16 in. deep a total rise in apparent temperature of 15°, extending over a tapping period of five minutes, is the usual experience. When the full stream of slag with a probable thickness of 4 in., appears a sharp rise at the rate of 15° in two minutes occurs. The first flush of steel cannot be observed owing to smoke, and the slag layer that formed the surface in the furnace before tapping has not been observed effectively, for it is necessary at that stage for the workmen to clean out the taphole with hooked rods. The ends of the gradient remain unexplored. Typical readings of a flow of the duration stated would be :—

	Apparent Temperature near Taphole.	Time, a.m.
Clear stream of steel	1,465	10.31
,, ,, ...	1,470	10.32
,, ,, ...	1,470	10.33
,, ,, ...	1,475	10.34
,, ,, ...	1,475	10.35
Last steel	1,480	10.36
Clear stream of slag	1,495	10.37
,, ,, ...	1,505	10.38
Last slag	1,510	10.39

The difference in the readings, for apparent temperature, of the last appearance of a clear stream of steel and the first full stream of slag varies with the time interval between the readings. For the same cast the apparent temperature at the end of the launder at 10.34½ was 1,470° apparent, while the reading for the slag at the same point at 10.39½ was 1,510° apparent. The slag temperature obtained at the end of the flow will represent a layer that was not far from the surface of the bath before tapping. Some difficulty has been experienced in determining the emissivity of these acid slags. Burgess found 0·65 for his dark slags, but this would give values much too low for the acid slags discussed in this paper. For the present it will be best to record the facts as observed and postpone a discussion until further investigations have been made. A difference in apparent temperature of 40° at the end of the launder is the average for a large number of casts. With this difference at the point where the observations were made the slag would represent the higher and thus rather hot layers, while the steel temperature recorded would be an average.

Variations in the Stream.

As the stream that leaves the end of the launder is on the whole the most convenient for observation it was necessary to determine whether all parts of the stream gave the same readings, and whether distance was a factor to be considered. Readings from a considerable distance were nearly always low owing to the difficulty in filling the field, and the effect of smoke and vapour, and afforded no compensating advantage. The stream itself gives varying readings both for slag and steel even when a full field is obtained, and here again it is perhaps better to state the facts and postpone a discussion of the probable reasons. The centre of the exposed side of the stream gives a lower reading than the bottom

TABLE II.

Observations of stream at end of launder		Position.	Pyrometer Readings Uncorrected. λ0·70 μ.									
	Steel	Top	1,465	1,470	1,470	1,460	1,475	1,470	1,470	1,475*	1,460	1,480*
		Middle	1,475	1,475	1,470	1,460	1,485	1,475	1,475	1,470	1,465	1,475
		Bottom	1,480	1,480	1,475	1,465	1,490	1,480	1,480	1,475	1,470	1,475
	Slag	Top	1,515	1,515	1,510	1,505	1,515	1,515	1,510	1,510	1,500	1,515
		Middle	1,515	1,520	1,515	1,505	1,515	1,515	1,515	1,515	1,505	1,515
		Bottom	1,520	1,525	1,515	1,510	1,520	1,520	1,515	1,515	1,505	1,520

* Deoxidized in ladle.

TABLE III.

Pyrometer Readings Uncorrected, λ0·70 μ.

Group of Moulds.	Time when Observations on each Group Commenced.	Apparent Temperature of Steel from Ladle Nozzle.	Apparent Temperatures showing Effect of Oxide Film. Steel.—Clean surface $\epsilon = 0{\cdot}40$; oxide film, $\epsilon = 0{\cdot}53$. Surface of Steel in Trough.			Apparent Temperature of Steel from Trough Nozzle.	Surface of Steel in Ingot Mould.	
			Centre near Stream from Ladle.	Intermediate.	Oxide film near End.		Centre.	Side.
1st	6·20	1,400	1,395	1,425	1,440	1,380	—	—
	6·25	1,398	1,400	1,435	1,440	1,395	1,390	1,425
2nd	6·31	1,396	1,398	1,430	1,440	1,390	1,390	1,425
3rd	6·36	1,394	1,395	1,430	1,435	1,390	1,390	1,425
4th	6·42	1,392	1,395	1,430	1,435	1,388	1,385	1,420
5th	6·48	1,390	1,390	1,425	1,435	1,386	1,385	1,420

when observed from the side, at an angle of about 45° with the axis of the launder, both for slag and steel, except when the deoxidizers are added in the ladle instead of the furnace, when the top of the exposed side often gives higher readings than the middle and bottom. The steels that have not been deoxidized before entering the ladle often have a film of oxide, which has a higher emissivity, on the upper surface. On the whole, having regard to the fact that the purpose for which the routine observations were made was to determine divergences from a normal, the centre of the exposed side of the stream nearest the end of the launder gave the best results and was adopted as a standard. A full stream of slag nearly always gave higher readings at the bottom edge of the exposed side than either middle or top, the exceptions being when bottom and middle were the same. Table II is a record of consecutive casts.

Thermal Losses.

There is a sharp drop in the readings when the clean surface of the steel in the ladle is compared with the stream flowing from the taphole. For an accurate determination of this difference it is necessary to recognize the gradual rise in the stream that issues from the taphole, for if the comparison be made between the ladle reading and that of the steel that issues last from the taphole the difference will be greater than if made with an earlier reading. The most consistent results will be obtained if the comparison be made with the standard readings at the launder end. The mean of a large number of observations was 30° apparent. This is the stage at which a serious thermal loss occurs, and affords the most convenient datum point from which the subsequent losses can be calculated. The turbulence within the ladle is always causing the contents to be well mixed by removing the cooling layers from the bottom and

TABLE IV.

Time.	Temperature of Steel in Ladle, Clean Surface.		Remarks.
	Apparent.	Corrected.	
6.10	1,450°	1,592°	
6.11	1,460°		$e=0{\cdot}40$.
6.12	1,460°	1,602°	$\lambda=0{\cdot}70\ \mu$
6.13	1,460°		

walls of the ladle. The loss, though considerable, is not more than would be expected. Once the liquid steel has been covered by its protecting layer of slag the thermal losses rapidly diminish after the first five minutes. The most accurate way to determine the losses during the casting operations is to observe a plane surface of the liquid steel when possible or a stream whose exposed surface has a considerable radius. Observations of a broad stream of steel falling over the open end of a spout, placed between the ladle nozzle and mould, give very consistent readings if a skimmer be used to prevent any oxide floating into the field of the pyrometer. If the observations be made on the surface of liquid steel in a small trough feeding two or more moulds, the conditions are

more complex. The stream from the ladle nozzle appears dark when compared with the plane surface of steel in the trough as a background and the apparent temperature of the plane surface is higher than the stream falling into it. If the plane surface be carefully explored it is found that the *clean* area near the falling stream is the same apparent temperature as the stream itself, as it should be in such a small trough, but as the field is shifted along the surface towards the end of the trough the apparent temperature steadily rises owing to the growth of a surface film with higher emissivity, until near the end an oxide layer is reached with a much higher apparent temperature. The apparent temperatures tabulated in Table III illustrate this very well. The ladle observations for the same cast are given in Table IV.

The Open-hearth Furnace as a Pyrometer.

Surprise is sometimes expressed that workmen can control their furnaces within the narrow temperature demanded by good practice in open-hearth steel manufacture. It happens that the hearth itself is a by no means inefficient pyrometer. The long flame, reaching nearly if not quite the length of the furnace, when using producer gas of regular composition, is approximately of constant average temperature and hotter than the walls and end blocks of the furnace. When the furnace temperature rises so that the flame cannot be distinguished from its background the melting range of the silica bricks has been nearly reached and if the temperature be maintained their fusion would result. The flame is therefore shortened until the temperature of the bricks becomes reduced, and the flame can be clearly distinguished. The control is therefore effected by noting the difference in apparent temperature of the flame and the exposed surface of the furnace walls and end blocks.

Conclusions.

In the manufacture of acid open-hearth steel a trained observer using a correct type of pyrometer can obtain readings of sufficient accuracy, when the necessary precautions are taken, to secure effective control of the process. Under the most favourable conditions the apparent temperature can be read to within $3°\pm$ and under normal conditions to less than $5°\pm$. As divergences from a determined "normal" are sufficient for this control these pyrometer readings can be used to determine temperature differences without importing any serious error.

The most suitable instrument is an optical pyrometer using monochromatic light $\lambda=0{\cdot}65\,\mu$, which it is suggested should be adopted as a standard. It should have a scale that can be read, under industrial conditions, to 2°. The observer should be able to read to $5°\pm$.

The thermal losses are small, when the steel has been covered with slag in the ladle, after the first five minutes.

The most consistent results are obtained when observing plane surfaces, or curved ones with a large radius, provided that they are not contaminated with molten iron oxide.

Observations on clean surfaces of liquid steel can only be made when the steel is in motion. Any determination of apparent temperature will therefore only refer to the particular surface that was under observation at the instant the reading was made. All such moving surfaces are rising or falling in temperature, so that the relative time at which the observation was made is an important factor when comparable results are desired.

OPTICAL PYROMETER CORRECTIONS TO ADD TO PYROMETER READINGS FOR EMISSIVITY.

Calculated from the formula—

$$\log 10^{\epsilon} = \frac{C \log E}{\lambda}\left(\frac{1}{T} - \frac{1}{S}\right).^{*}$$

Wave-length = 0·70 μ.
ϵ = emissivity.
C = constant, 14,500.
E = Naperian base, i.e. log E = 0·4343.
T = true temperature absolute.
S = observed temperature absolute.

CORRECTIONS TO ADD TO PYROMETER AT VARIOUS TEMPERATURES AND EMISSIVITIES. μ 0·70. †

Pyrometer using Red Light.

(S. F. B.)

ϵ = Emissivity.	Temperatures observed.						
	1,350°.	1,400°.	1,450°.	1,500°.	1,550°.	1,600°.	1,650.°
0·40	125	134	142	151	160	169	179
0·50	93	99	105	112	118	125	132
0·60	68	72	77	81	86	90	95
0·65	57	60	64	68	72	76	80

POSTSCRIPT.

It has been suggested that the apparent temperatures in Table I were obtained under conditions so nearly approaching those of a " black body " that no corrections were necessary. The reply is that the large doors were wide open and that every detail of the brickwork could be seen distinctly. It has also been pointed out that though " black-body " conditions were absent, yet reflection of incident radiations from one heated surface by the others would be so considerable that the usual corrections for a free radiating incandescent surface would not apply. It must be admitted that a certain amount of reflection does take place, but it is also certain that the real temperature of furnace interior varies in the order of the differences indicated by the apparent temperatures in Table I, and that if the real temperature of one of the brickwork surfaces could be determined, the others might be calculated. The corrections actually applied in Table I are probably too high. The apparent temperature of the bath surface was observed with the gas off and door up, and the surface observed was near the door, so that the conditions closely approached that of a free radiating surface. The only really doubtful factor there would be the emissivity adopted.

* The formula is taken from Technologic Paper, No. 91, Bureau of Standards.

† As the observations recorded in this communication were made with a pyrometer using a wave length of 0·70 μ, and as many other pyrometers using the same wave length are probably in use in various works this table of corrections was computed.

NOTES ON PYROMETRY FROM THE STANDPOINT OF FERROUS METALLURGY.

Dr. W. H. Hatfield (Sheffield) contributed the following "Notes on Pyrometry from the Standpoint of Ferrous Metallurgy."

Having accepted the invitation to take part in this discussion, the author feels that he cannot do better than deal with the subject from the steelworks standpoint. It will be appreciated that in large armament works, such as the ones with which he is associated, the adequate control of temperature in metallurgical operations is vital. It may, therefore, be of interest to members of the Society to receive a commentary upon their experience of the means available and the difficulties to be encountered.

One important section of the Brown-Firth Research Laboratory is devoted to the standardization and maintenance of the pyrometers used throughout their different works, and, needless to say, one of its functions is to follow closely the development of pyrometry. These notes may, therefore, be taken to indicate their point of view as regards the most useful types of instruments for different purposes, and the author will look forward to the discussion with considerable interest.

All operations, melting, forging, rolling, annealing, hardening, tempering, etc., are best executed within some particular range of temperature, owing either to the influence of such temperature upon the actual operation or upon the subsequent properties of the material. In the first place the most suitable range of temperature must be determined, and subsequently efficient means must be found for accurately repeating, for an unlimited number of times, the treatment so determined. For the investigatory side of the work, temperature readings should be preferably in absolute values; for industrial processes the instrument need not necessarily give such values directly, but those actually recorded should be readily transposed into absolute values. Having secured instruments capable of accurate measurement, the next step—and it would appear to be merely a re-statement of a platitude—is to see that the actual temperature of the mass under observation is obtained. This is essential and by no means easy in a works, unless the instrument is used most intelligently by the individual under whose control it is placed.

The Measurement of the Temperature of Molten Steel.—Although the temperature at which steels are cast must have an influence upon their ultimate physical properties, no ready and really reliable method for measuring such temperatures from the works standpoint is available. This is a considered statement. What is meant by it is this, viz. that

the temperatures of molten steel can be, and are, determined experimentally, but it is quite a different matter to obtain, in works practice, ready readings which may be unimpeachable and represent, or be readily converted into, absolute values. An optical pyrometer directed on to the slag, or on to the walls and roof of a furnace, will certainly give indications of the temperatures of the areas sighted upon, but the author is quite in agreement with the recently expressed opinion of Mr. Burgess, of the Bureau of Standards, Washington, that there is no satisfactory relationship between the temperature of the furnace chamber and slag, and the metal lying in the hearth. Probably a study of the emissivity of different slags might lead to useful information and assist in some of the corrections necessary, but it should always be remembered that the heat in such a furnace as the Siemens passes through the slag to the steel. It may, however, be of interest to describe here one of two experiments made upon uncovered molten steel with a view to testing the readings obtained from pyrometers available.

It would obviously be of considerable use if the temperatures of successive heats of steel could be controlled and determined. The author has carried out experiments with a number of heats by means of the thermoelectric pyrometer and also with the Cambridge optical one. The optical pyrometer was sighted upon the steels running into the ladle and, to take one or two instances, the values obtained were in the neighbourhood of 1,400° C. to 1,410° C. (low and high range scales for the same instrument). Turning now to the comparative readings with the thermocouple pyrometer, a couple was placed in position in the empty ladle prior to the steel being run in. As the steel gradually filled the ladle the temperature indicated by the thermocouple increased until the couple was thoroughly immersed in the molten steel. The steel now was tapped from the ladle, the metal receding until the couple was quite free from the molten steel. It will be seen that by this means a time-temperature curve was obtained in which a flat maximum range was observed, corresponding to the temperature of the steel whilst in the ladle. It may be of interest to state that the values so obtained ranged from 1,600° to 1,625° C. These values are not put forward as absolutely correct temperature determinations, as extrapolation beyond 1,400° C. is still a matter of some uncertainty with these couples, but it is believed that the figures stated are reasonably correct. It was considered that there was a difference of something like 150–200° C. in the two kinds of readings, and the temperatures so stated may be taken to indicate the apparent disparity between the two methods of approach. It is fully appreciated that a correction is necessary in the case of the optical pyrometer for imperfect black body conditions, but it would seem necessary that such a recognized variable error will have to be put upon a quantitative basis before optical readings can be thoroughly utilized where small variations at very high temperatures are important. One problem, for instance, is of considerable interest, viz. does the emissivity of steel vary with the condition independent of temperature ?

Whilst dealing with the question of molten steel it may be of interest to record that with the thermocouple method the freezing temperatures of steels have been industrially determined by us, and that, for instance, with a 0·1 per cent. carbon steel the temperatures so obtained are 1,480° to 1,485° C., such values being in sufficient conformity with the present iron-carbide diagram. The author has stated the preceding experiences with the object of eliciting from other investigators any

data which they may have concerning the actual temperatures of molten steel, since, at the present time, there is very little published information.

Re-heating.—For such work we generally use platinum–platinum-rhodium thermocouples in vitriosil tubes for temperatures up to 1,100° C. We also employ the Cambridge optical pyrometer. This optical pyrometer gives results strictly comparable with thermocouple readings when the steel body is in the furnace, but naturally reads low when the object sighted upon is placed in the open air, owing to the black-body conditions under which the test is made not being realized in the latter case. However, if the conditions of the tests are kept consistent the readings from the optical instrument, whilst they must be checked by transposition to absolute temperatures, yield a ready means of checking temperature in such works operations. If considerable care is exercised it will be found that the temperature of a mass of steel in the furnace will be recorded as 60° to 100° higher than the temperature of the same mass of steel when taken outside the furnace, this difference existing after allowance has been made for the conditions of the determination.

Forging and Rolling.—Determination of the temperatures of steel bodies undergoing forging and rolling operations presents another interesting problem. It is sometimes claimed that with suitable corrections the readings of an optical pyrometer will give all that is required, and that the readings themselves might be comparable with one another. This, however, does not quite state the whole of the case. In forging, particularly, the hot body has a large area in intimate contact with the large masses of steel forming the hammer and die, and as the body is rotated during the forging operation the outside becomes considerably cooled. For instance, take a 15-in. ingot, 3 or 4 ft. long. The temperatures of the surface towards the end of a forging operation would give an indication, say, in the neighbourhood of 900° C., whilst if the same ingot were then cut in two and immediately sighted the inside would be found to be at a temperature of, say, a little over 1,000° C.

Annealing Operations.—Whilst the thermo-electric pyrometer forms an accurate, convenient, and easily adjustable instrument, sufficient attention is not always given to the manner in which the couple is placed relative to the steel. This comment really applies to all operations which involve the heating up of masses of steel. It is their practice to determine time and temperature data which will give practical information for the man in charge of the operation, by putting through experiments with masses of the same size. In such experiments one thermo-couple is placed inside the mass whilst another is placed outside. However, it has already been pointed out that it is a relatively easy matter to obtain an instrument capable of consistent recording of temperature, and it is up to the works man to see that he determines that temperature of his material which is actually required.

It is noted that Dr. Arnold is going to deal with the temperatures involved in the hardening of high-speed steel, and this matter will, therefore, be left. It may only be said that either an optical pyrometer intelligently used or a properly standardized platinum–platinum-rhodium thermocouple adequately meets the case.

Base-metal Couples.—It may be of interest to state that experiments which we have conducted over a considerable period have led us to the conclusion that we may safely and economically employ silver-constantan and nickel and nickel-chrome couples in low temperature work.

The Heating of the Mass of Steel.—Having briefly discussed the technique of the control of temperature in the works, the author proposes to discuss the question of heat penetration. Here we have an important field of investigation open to all those interested in research. By practical experiment and careful observation the technique as regards temperature control in a modern steelworks is of a high standard, but the desire is always present with the scientific man to replace, if possible, empirical methods by the results of quantitative deduction. Different steels may respond differently as regards time and temperature, and it is obviously desirable that the applied scientist should be able to predict any diverse behaviour to be expected from different materials. When faced with this problem the data upon which he has to work are those provided by the pure scientist.

The physical characteristics of the material which are involved in this question of the velocity of heat penetration are its thermal conductivity, its specific heat, and its density, which between them furnish the quantity referred to as the " diffusivity " of the material. It is found by experience that the time required to heat up and thoroughly soak a given mass varies considerably with the nature of the material, as well as with its shape and dimensions. This would be expected from a study of variation which occurs in the physical constants. It is very desirable for many purposes that we should be able to predict the thermal condition of a mass at any given time from the commencement of heating. By its condition is meant the existing temperature at all points throughout the mass.

A hypothetical type of curve of temperature through the mass at an early stage of the heating may be conceived, assuming that the heat is supplied from a reservoir kept by some means at a fairly uniform temperature. It is then extremely difficult to deduce the subsequent modifications with time. It is suspected that there is a sudden drop of temperature, or at any rate a very steep gradient at the skin of the material as well as just inside the boundaries of the heating reservoir. This is an interesting point, and deserves discussion. The quality of the surface itself plays some part in determining the rate of absorption of heat. Incidentally the heating medium of the reservoir is of fundamental importance. The problem is having attention, and a further paper will be given dealing with this phase. A consideration of the problem is somewhat complicated by the fact that the physical constants involved vary, as the temperature rises, in a manner not yet fully determined. Moreover, as the different portions of the mass reach their "critical points" new waves of "cold" will be imposed on the hitherto smooth temperature curve.

Much interesting matter has been contributed by various workers in this field, notably that of Dr. Harker, J. W. Richards, and others, on the specific heat of iron at varying temperatures. From Dr. Harker's experiments it appears that the specific heat of nearly pure iron increases steadily from ·1175 at 200° C. to ·1647 at 850° C., beyond which temperature there is a slight decrease. Similar information for steels and various alloys is at present very meagre, and there is room for much further detailed research.

The determination of thermal conductivity of various materials has been attempted by numerous methods, nearly all of which call for elaborate precautions, calculations, and corrections in order to obtain exact values. The earlier work of Wiedemann and Franz, Forbes

Gray, and Mitchell are typical of this. The method of Angström, in which the rate of travel of waves of heat and cold along a bar is measured, has the advantage, for the purpose under consideration, of giving directly the value of "diffusivity."

A very simple method, suitable for comparative tests, is that adopted by Mr. A. Johnstone, B.Sc., and described in a paper recently presented to the Physical Society. He employed his apparatus for measuring changes in thermal conductivity which take place when the material is stressed. A known amount of heat is supplied at the centre of a wire, whose ends are kept at a constant cold temperature. The temperature gradient along the wire is measured. Mr. Johnstone has shown that under these circumstances, with the dimensions of wire employed, simplified calculation is obtained by making very slight approximations, which are equivalent to neglecting the amount of heat radiated from the wire under test.

An apparatus constructed on this principle, but in which the proportional radiating surface was still further reduced, has been used at the Brown-Firth Research Laboratory, and it may be of interest to quote some of the results. The samples tested were bars 1 cm. diameter, and the fall of temperature along the bar was measured by copper-eureka thermocouples. A few of the results obtained are:—

Material.	Relative Thermal Conductivity.	Relative Electrical Conductivity.
Wrought iron	100·0	100·0
0·9 per cent. carbon steel, as rolled ..	65·3	58·4
25 per cent. nickel steel	25·8	12·25
Air-hardening nickel-chrome steel, as rolled	40·6	34·5
High-speed steel, as rolled	38·0	36·2
High-speed steel, hardened	28·8	17·2

These results are only at room temperature over a range of 10° C. to 40° C., and the electrical conductivities are given for comparison. It has been usually considered that thermal and electrical conductivities follow each other very closely, and it has been suggested that in accordance with the electronic theory of conduction the ratio between the two should be quite constant at a given temperature, and increase in proportion to the absolute temperature. Experiments by Jaeger and Diesselhorst show that the relation is only very approximately satisfied in a comparison of different metals. The above figures emphasize that point of view, and indicate only rough agreement among different kinds and conditions of steel.

The author has endeavoured to present this general question of temperature control as it appears to him in the light of his daily practice, and he hopes that some of the points which he has raised may be of service to those who are devoting their time and attention to the improvement and application of pyrometrical apparatus. It is his opinion that there is a great deal to be done, and there is no direction in which the scientific worker can be of greater use to the

steel manufacturer than to place in his hands means of accurate and easy determination of temperature. At the same time it is hoped that attention has been drawn to several different directions in which error can enter into temperature determinations through lack of knowledge or appreciation on the part of the man in the works. Pyrometers should be judged upon their actual performances, and care be taken not to charge to the maker of the pyrometer errors which can obviously be shown to lie in the manner of their application.

APPLICATIONS OF OPTICAL PYROMETRY IN STEEL WORKS PRACTICE.

The following Paper on "Applications of Optical Pyrometry in Steel Works Practice," by **Mr. J. Neill Greenwood, M.Sc.**, was communicated after the meeting.

Having heard with great interest the views and experiences of several workers in the industrial applications of pyrometry, the writer would like to give his own experiences in the same field, since in some respects he has not been so successful as several of the speakers, especially in connection with optical pyrometry applied in steel-making.

Since optical pyrometers are calibrated under black-body conditions, it is well at the outset to examine the working conditions at the steel furnace, to see in what respects and to what extent these differ from the calibration conditions.

1. *Emissivity.*—A true black body (by definition) is one which absorbs all radiation falling upon it, and the radiation emitted by such a body is a function of its temperature only. Taking the radiation from unit area of a black body at a given temperature as unit, the energy from any other body at the same temperature is given by $e=a=1-r$, where—

a=amount of monochromatic radiation absorbed by the body at the given temperature.

r=amount reflected (under same conditions).

Hence, if the body whose temperature is being measured is a good reflector, it must by the above relationship be a poor absorber, and consequently at any given temperature the amount of radiant energy emitted by unit surface will be considerably less than that emitted by a black body at the same temperature.

Polished metals are in general good reflectors, and liquid metals having a clear surface are also good reflectors. Hence we find that optical pyrometers sighted upon polished or clear liquid metals give black-body temperatures which are considerably lower than the actual temperatures. On the other hand, suppose in taking a temperature of a stream of metal a direct beam of sunlight strikes the area sighted upon, a large part of the incident beam will be reflected, and it is quite conceivable that appreciable apparent rises in the black-body temperature could result. Perhaps even a neighbouring arc-lamp would cause disturbances.

2. *Wave-length of Light employed in Comparison.*—In the Wanner pyrometer the light from the standard source and from the hot body is analysed spectroscopically, and a definite band (approximately monochromatic) is chosen in the red, for the purpose of comparison. In such a case there is no trouble, as light of the same length is always selected, but if instead of this method an absorbing screen is used, the light transmitted is generally far from monochromatic; in fact, a red glass will

usually transmit light of $\lambda = \cdot 60\ \mu$ to $\lambda = \cdot 70\ \mu$, and I understand that in certain cases light of $\lambda = \cdot 56\ \mu$ is transmitted.

Now the temperature of the comparison source (the electric filament) remains constant, and hence the relative intensities of the light of wave lengths in the particular spectral band transmitted by the screen from that source is also constant, but the temperature of the outside source is not constant, and the higher it is the shorter is the wave length of maximum energy, for we have the relationship $\lambda_{max.}T = \text{constant}$. Hence the *relative* intensities of the light of various wave-lengths transmitted by the screen changes with the temperature, and this causes variations of tint in the two halves of the field, with consequent difficulties in adjusting the intensities to equality.

3. *Polarization of Emitted Light.*—It is well known that both reflected and emitted light, except that reflected or propagated in a direction normal to the surface, are plane polarized, and this to a greater or smaller extent according as the divergence of the ray from the normal is greater or smaller. It follows that unless the object whose temperature is being measured is viewed normally, the light entering the pyrometer is already partially polarized, and the readings are consequently affected. As has been pointed out by Waidner and Burgess,* the effect can be eliminated by rotating the instrument axially, and taking readings every 90°. The average will then be free from polarization effects.

4. *Fumes.*—The intensity of the light arriving at any point from a given source, depends upon the absorbing power of the medium between the two. This is obvious when one remembers the diffusing power of fog or clouds on sunlight. Hence anything in the nature of water-vapour or finely divided oxides, between the object emitting light and the pyrometer, will cause low readings owing to diffusion of the light.

5. *Size of Source.*—If the source whose temperature is to be taken is not sufficiently large to fill the photometric field of the pyrometer (when the latter is placed at a reasonable distance), it is exceedingly difficult to effect a comparison. Apart from this, however, the readings obtained are low, due to some cause of which the writer is not aware

Examining now these various effects from the point of view of obtaining the true temperature of the object, we find at once that they fall into two classes:—

(*a*) Those definite physical quantities of which the magnitude is known and which can be corrected for, e.g. emissivity and polarization of emitted light.

(*b*) Those indefinite and variable sources of error for which it is impossible to make any correction, e.g. variation in tint of the two halves of the photometric field, due to lack of monochromatism of the absorbing screen, absorption of light by the intervening medium, and failure to fill the photometric field.

Magnitude of the Corrections and Errors involved in the taking of the Temperature of Liquid Steel by an Optical Pyrometer directly.

It is assumed that the pyrometer is sighted on the liquid metal in the open.

For light of wave-length $\lambda = \cdot 65\ \mu$ the emissivity of polished and liquid iron is ·415,† hence the black-body temperature of liquid steel

* *Bulletin of Bureau of Standards*, vol. 1, p. 253.

† Burgess and Le Chatelier, *Measurement of High Temperature*, p. 497.

is 120/180° C. higher than that indicated by the pyrometer (apart from other corrections).

Mr. Cosmo Johns has given a very useful table at the end of his paper, showing the emissivity correction for various "apparent temperatures," and for various emissive powers, the wave-length selected being $\lambda = \cdot 70\ \mu$. The correction is obtained by evaluating Wien's law in the form

$$\frac{1}{T} - \frac{1}{T'} = \frac{\lambda \times \log a}{c \times \log \epsilon},$$

where—

T = true black-body temperature degrees absolute.
T' = apparent black-body temperature degrees absolute.
λ = wave-length of light selected for comparison.
$a = e$ = emissive power.
$c = 14{,}500$.
ϵ = base of natural logs.

It will be noticed that the correction involves λ. Hence it can only be strictly applied in such pyrometers as the Wanner, in which a definite wave-length is optically selected, and conversely no strict correction can be applied to the readings obtained with types using an absorbing glass, e.g. Le Chatelier and Cambridge optical pyrometers. To show the magnitude of the possible error in such cases, assume an apparent temperature of 1,427° C., then, assuming $\lambda = \cdot 65\ \mu$, we get 1,549° C. as the true temperature, whilst, assuming $\lambda = \cdot 70\ \mu$, we get 1,558° C. Since, as stated above, the red glasses employed transmit light of wave-lengths between ·60 and ·70 μ, it is obviously impossible to arrive at a true temperature with such instruments with a greater accuracy than 10° C. For most purposes, however, it is only desired to know the relative temperature of various casts, and in such cases this factor would not give any trouble. Sooner or later it is bound to become necessary to know the actual temperature of the molten steel, and so it is as well to know which pyrometers are suitable for this class of work, having due regard for general conditions.

As regards the effect of polarization there seems to be no data available for liquid steel. In this respect, however, it should be noted that for polished metals such as platinum, silver, and gold, the effect can cause an apparent variation of temperature of 40° C. at 1,450° C., when the angle of view is 50° from the normal. And since liquid steel having a clear surface can be classed as a polished metal, it is probable that variations of the same order occur in this case also. In fact, by taking readings in four quadrants—rotating the scale of the pyrometer through 90° for four successive readings—the writer has obtained variations of 50° C. (apparent) from the mean reading, when the angle of inclination to the normal was 70°. Time has not permitted a systematic research on the point up to the present, and so no definite magnitude can be assigned to this source of error. There are two methods of eliminating it.

(*a*) By viewing the stream normally—since the light propagated normal to the surface is not polarized.

(*b*) Keeping the angle of inclination the same, rotate the optical system and take readings in four positions at right angles. The mean result is then free from polarization errors.

Passing now to those indefinite sources of error mentioned above, it has been found * that, provided the absorption glass does not transmit

* Burgess and Le Chatelier, *Measurement of High Temperature*, p. 222.

light other than that between the limits $\lambda = \cdot 60\ \mu$ to $\lambda = \cdot 70\ \mu$, there is no trouble due to variation of tint when the temperature is below 1,300° C. to 1,400° C. Outside these limits of wave-length, or within these limits at higher temperatures, it is quite possible that serious difficulty would be encountered in matching the intensities of the two halves of the field. This difficulty might pass unnoticed in the primary calibration (unless it was very marked), for above 1,550° the only possible calibration is obtained by calculations based on the radiation laws.

The presence of fumes of varying diffusing power in the atmosphere surrounding a stream of molten steel is perhaps the greatest variable which is encountered. Mr. Cosmo Johns recommends keeping to the windward side of the stream. It is the writer's experience, however, that the wind is as great a variable as the fume. In the first place there is often insufficient wind to keep one side of the stream free from fume, and on the other hand, in the neighbourhood of furnaces, it often happens that the wind selects two or three different passages at once, and in such cases it is difficult to choose the " windward " side.

Having thus briefly reviewed the difficulties inherent in the *conditions* of use, and *principles* involved, which the writer has come across in attempting to measure the temperature of liquid steel by means of an optical pyrometer, a word or two might be said regarding instrumental defects.

The particular pyrometer referred to is the Cambridge optical pyrometer, making use of a polarizing device for equalizing the intensities of the two halves of the field, the standard source of light for comparison being a four-volt lamp, through which a standard current is passed (determined periodically by comparison with an amyl acetate flame). Starting from the assumption that the pyrometer is to be used in an industrial establishment—*not free from vibration*—it can be reasonably demanded that all connections in the standard light circuit shall be stoutly made, and sliding contacts shall have a high frictional coefficient. Many temperature determinations have been rendered valueless owing to these demands not having been fulfilled. For example, in taking temperatures of a liquid stream it has sometimes been necessary (for the sake of personal comfort) to move the pyrometer and its tripod, and although the box containing the accumulator, ammeter, and rheostat has not been moved, the moving of the flexible wire has caused big variations in the standard current. This was early found to be due to a loose connection inside, connecting the plug to the ammeter. When working in the neighbourhood of a steam hammer (in which case one can overlook temporary movements of the pointer) the vibration has often caused movements of the contact on the rheostat, thus giving rise to variations of the standard current. This and similar sources of trouble have spoiled several series of temperatures in which it was essential to obtain a rapid succession of readings, owing to the necessity of adjusting the current.

It will be well to consider here another point which limits the accuracy of the readings in this type of pyrometer, viz. the accuracy with which the standard current can be adjusted. Experience has shown that this is of the order of a half of one division on the scale. Now a variation of this magnitude corresponds with a temperature equivalent of $\pm 5°$ C. at 1,000° C. Hence from this point alone the limit of accuracy is $\pm 5°$ C.

Several questions arising out of the papers read call for discussion at this point.

First of all, Mr. Johns has asked for a pyrometer having limits of accuracy of $\pm 2°$ C. at 1,500° C. The results he has given are truly remarkable, and it would be of great value if he would say what type of pyrometer he used. It seemed to the writer that Mr. Johns must have almost ideal conditions at the steel furnace to obtain such consistent results, even taking the precautions set out in his paper. Normally the conditions are more likely to be as above described, but even allowing for ideal industrial conditions, it appears from the above analysis of the possibilities of error to be quite beyond the present attainments of a polarizing optical pyrometer (especially if using a selective absorbing screen) to have a higher order of accuracy than $\pm 5°$ C., and under most works conditions the limits would be far wider than this. In fact the conditions prevailing in certain works are such as to make observations on liquid steel surfaces useless from a quantitative point of view.

It should be clearly understood that it is the *conditions* which are chiefly at fault, and not the *pyrometer*.

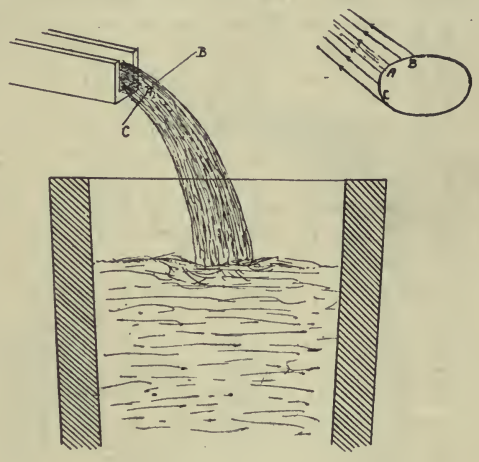


FIG. 1A.

FIG. 1.

Dr. Hatfield had mentioned that readings which he had taken with the thermocouple gave a temperature some 200° C. higher than the black body temperature as given by the optical pyrometer, and he had asked for the reason of this. A summary of the possible errors is given in Table I, and from this it is clear that errors of the magnitude mentioned by Dr. Hatfield are to be expected. The table is primarily concerned with the Cambridge optical, but it will be seen that most of the items concern all types of pyrometer utilizing the polarizing device. A glance at the table shows at once that direct readings with an optical pyrometer on liquid steel are subject to a correction of the order of 200° C. (if the first and third effects are additive—a point which will depend on the relationship between the plane of polarization of the emitted light and the polarizer in the instrument). The errors due to fume absorption and failure to fill the field will be in the same direction as that due to low emissivity, whilst opposing these is the correction due to light reflected from external sources (which normally will be negligible).

Mr. Johns referred to apparent variations in temperature in different

TABLE I.

Sources of Error in taking the Temperature of Liquid Steel directly with an Optical Pyrometer.

Source of Error.	Nature.	Magnitude.	Remarks.
Emissivity of liquid steel ..	Optical	120° C. to 180° C.	Depending upon (1) the wave length of light used in comparison, and (2) the temperature of the steel.
Reflection from external sources	ditto	Variable	Depending entirely upon the intensity and situation of the disturbing source. Negligible under normal diffused light conditions.
Polarization of emitted light	ditto	0° C. to 50° C. (probably)	Depending upon the divergence of the angle of view from the normal.
Lack of monochromatism of the absorbing screen	ditto	—	Makes it impossible to correct exactly for emissivity. For the band $\lambda = \cdot 60\,\mu - \lambda = \cdot 70\,\mu$ the accuracy of this correction is $\pm 10°$ at 1,550° C. For wider limits or higher temperatures variation in tint will cause comparison difficulties.
Absorption by medium (due to water vapour or fume)	ditto	Variable and indeterminate	——
Failure to fill photometric field	Conditional	Variable	Useless to attempt a comparison unless the greater part of the field is filled with light.
Standard current adjustment	Technical	$\pm 5°$ C.	In the case of the Cambridge optical assuming accuracy of adjustment ·5 division.

parts of the stream. These can readily be explained by the principles set out above. In Fig. 1 is shown a stream of metal running from the furnace. A cross-section of this will be approximately elliptical, as shown in Fig. 1A. The position "A" is the one chosen by Mr. Johns for his reading. It will be seen that the beam of light from this part of the stream is almost wholly normal to the surface, and therefore polarization effects will be negligible. On the other hand, from the positions B and C the light deviates considerably from the normal; in fact light from the extreme edge will be almost wholly plane polarized. Hence temperatures taken from the two outsides will be considerably different from those taken in the middle of the stream. As regards the temperatures on the under side of the stream being higher than those on the top, it is very likely that this is due to reflection from the hot metal in the ladle.

Suggestion for improving the Experimental Conditions at the Furnace.

Having arrived at the conclusion that the conditions obtaining when sighting upon a stream of liquid steel are subject to great and variable

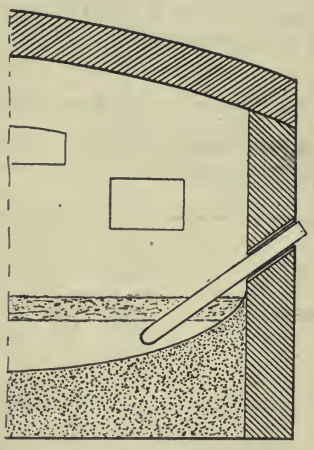


FIG. 2.

deviations from the conditions of calibration of the instrument, it will be advisable to consider how the conditions could be improved.

At the outset it must be stated that the writer has not had time or opportunity to attempt to put any of the following suggestions into practice.

Three main points should be kept in view:

1. In order to *control* a process it is necessary that the control should operate simultaneously with the process, and not when the latter is finished and all chance of rectification is gone (such as is the case when the temperature is taken as the metal is running from the furnace).

2. The steel-maker is concerned primarily with the making of the steel and not with the taking of its temperature.

3. Any alteration of the present methods should be towards obtaining a nearer approach to black-body conditions, and the elimination of as many as possible of the errors mentioned above.

The first point enforces the necessity of taking temperatures of the

metal whilst it is in the furnace. So far this has proved to be an impossible task, owing to the unknown physical properties of the slag covering (heat conductivity and emissivity chiefly), and the disturbing effects of flames.

The second point shows why one cannot shut off the gas periodically —as this would endanger not only the particular cast of steel, but the whole furnace.

The third point suggests a way out of the difficulties. It is suggested, namely, that a black body be made in the bath whenever it is required to take a temperature. The proposed method is illustrated in Fig. 2. The exact details would, of course, vary with the type and dimensions of the furnace. A tube of refractory material is pushed below the surface of the bath as indicated, so that the end and some 6 inches of the length is actually in the molten steel. The optical pyrometer could then be sighted on the end of the tube, which would form an almost perfect black body. The tube would need to be diaphragmed in order to cut off the light from the sides, as these would be hotter than the end. There are many obvious and probably still more hidden difficulties in this method, but it seems to the writer that there are none which would be insurmountable. In such an event the optical pyrometer would become an invaluable asset to the steel-maker.

Optical Pyrometry in the Heat-treatment of Steel.

The use of the optical pyrometer is much simpler when the heat treatment of steel is under consideration, for under normal manufacturing

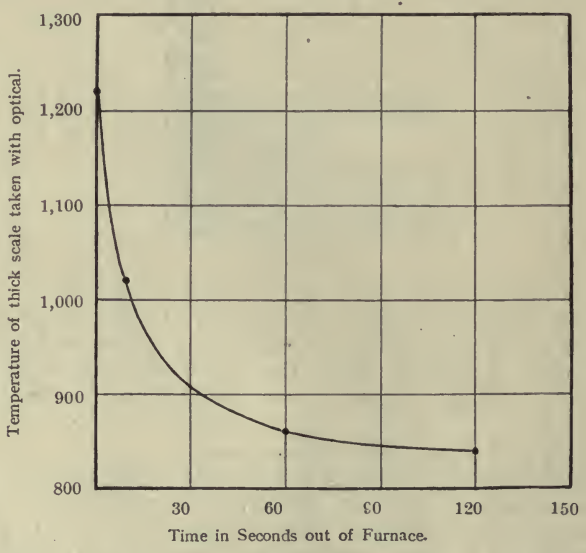


Fig. 3.—Showing Sudden Fall in Temperature of Outer Oxide Scale on Large Ingot on Removing from Furnace.

conditions the steel is invariably covered with an oxide layer (of variable thickness) and iron oxide approaches very near a black body, hence the correction due to departure from true blackness is very small, amounting

to no more than 5° C. at 1,000° C.* But whilst the presence of iron oxide with its high absorbing power removes one difficulty, it introduces another owing to its low thermal conductivity. That is to say, although the temperature of the outer oxide surface can readily be determined to within a few degrees by optical means, it does not follow that the metal immediately beneath the oxide has the same temperature, and when one considers that it is the temperature of the steel which is required, it is at once necessary to know the magnitude of this effect.

By way of example a few typical cases have been chosen to illustrate this point. These are given in Table II. A refers to a large ingot taken

TABLE II.

Remarks.	Times.	Last Temperature in Furnace.	Temperature on Thick Scale.	Temperature under Thick Scale.	Temperature difference.	
		° C.	° C.	° C.	° C.	
A	9·49	1,265	—	—	—	Out
	9·50	—	910	—	—	
	9·52	—	890	—	—	
	9·54	—	—	985	95	
	10·17	—	750	880	130	
	10·25	—	750	860	110	
B	3·0	1,220	—	—	—	
	3·10	—	1,020	—	—	Coming out of furnace
	3·11	—	860	—	—	
	3·12	—	840	—	—	
	3·13	—	—	1,060	220	

from the furnace at 9.49. It will be seen that just before removing from the furnace its temperature was 1,265° C., and since the furnace walls were at the same temperature and the ingot had been thoroughly soaked, this may be taken as the actual temperature of the metal at the time of drawing from the furnace. But one minute after withdrawal the temperature of the outer scale was only 910° C., and after another two minutes the temperature had fallen another 20° C., i.e. in the first minute the temperature of the ingot apparently fell 355° C., whilst in the succeeding two minutes there was only a fall of 20° C. When, however, the thick scale was removed by pressing there was an immediate rise of 95° C. in the reading of the pyrometer. When (30 minutes after withdrawal from the furnace) the temperature of the scale on another part of the ingot had fallen to 750° C., on removing the scale rises of 130° and 110° C. respectively were noted. (This relative discrepancy is accounted for by sighting difficulties.)

Example B refers to an exactly similar type of ingot, but a reading was obtained ten seconds after withdrawal from the furnace in this case.

* Burgess and Foote, *Bul. Bur. Standards*, vol. 12.

The relationship between temperature of scale and time in the open air is shown in Fig. 3. This curve has merely been drawn through the observed points to assist in visualizing the case and not to suggest any mathematical relationship, the general conditions being too uncertain to make this possible. From this it is seen that within a few seconds of withdrawing from the furnace the temperature of the oxide scale falls several hundred degrees C.

TABLE III.

Temperature Gradient in Oxide Film.

Observed Temperature (Oxide) $\lambda = \cdot 65\ \mu$.	True Temperature (Metal).
° C.	° C.
600	612
700	712
800	818
900	933
950	1,000
1,000	1,080

TABLE IV.

Time out of Furnace.	Temperature of Scale.	Time out of Furnace.	Temperature under Scale.	Difference.
Min.	° C.	Min.	° C.	° C.
13	830	12	975	145
2	840	3	1,060	220
4	860	5	940	80
8	860	7	965	105
2	880	5	985	105
2	925	3	1,040	115
1½	930	2½	1,100	170
2	940	3	1,040	100
—	960	2	1,070	110

In this case there was a rise of 220° C. when the scale was removed. Hence we see that the low thermal conductivity of iron oxide is a serious matter in taking the temperature of ingots in the open, for the greater the thickness of the scale the greater the temperature difference between the outer surface and the metal immediately underneath it. Unfortunately the thickness of the scale is not the only variable. Owing to fluctuations of the temperature in the furnace, etc., the thick scale often parts from the metal, and an air layer then exists between the two. This further increases the temperature difference—air being a notoriously bad conductor of heat.

In the cases quoted the oxide layer was several mms. thick. Even when the main scale has broken away the true temperature of the metal is not obtained. Now, however, the oxide film is much thinner, and will be comparatively uniform in thickness, and under these conditions it is possible to apply the correction found by Burgess and Foote,* who measured the temperature gradient between metal and oxide surface, the temperature of the metal being taken by thermocouple, and that of the oxide by an optical pyrometer.

These corrections, given in Table III, have been taken from the above paper, and it will be seen that they are in no way negligible.

As will be seen from Table IV, random temperatures taken of scale and metal underneath show no consistent difference. This is undoubtedly due to variations in the thickness of the scale.

Effect of Reflection from Flames on Temperatures taken in Reheating Furnace.

Since iron oxide is not a perfect black body it is necessary to determine whether it is a sufficiently good reflector to cause appreciable error in

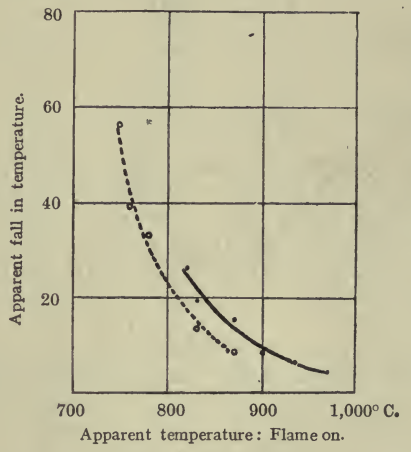


FIG. 4.—Effect of Reflected Light on Readings of Optical Pyrometer Sighted on Iron Oxide.

Full curve relates to compact lustrous oxide.
Broken curve relates to natural oxide.

taking its temperature in the presence of luminous flames. Some work has already been published by the Bureau of Standards on this point, but it is not in a form which can be interpreted in terms of industrial conditions. Accordingly the following series of experiments was conducted with a view to determining the correction necessary under furnace conditions.

A block of steel, approximately 12 in. × 9 in. × 5 in., was heated in a gas-fired furnace (3 ft. × 2 ft. 6 in. × 2 ft.). Temperatures were then taken with the optical pyrometer, both with the flame full on, and then with practically no flame. The results are shown in Table V.

These results are also shown graphically in Fig. 4. It will be noticed that up to 900° C. there is a considerable increase in the pyrometer read-

* Loc. cit.

ing, due to reflection from the flame. It should be mentioned that each of the temperatures given in the above table is an average of six readings often taken by two observers. Above 900° C. the correction is negligible.

The surface referred to, i.e. the one on which the pyrometer was sighted, was, in the cold, the black, compact, lustrous oxide, which is

TABLE V.

Optical Pyrometer Sighted on Compact, Lustrous Oxide Surface Formed in Pressing.

Temperature with Gas on.	Temperature with Gas off.	Difference.
° C.	° C.	° C.
820	794	26
833	814	19
872	857	15
902	894	8
936	930	6
970	966	4

seen on forgings. It was this lustre which first suggested to the writer that it might be a good reflector. Having taken this series of readings, a similar series was taken on a "natural" oxide surface, which had formed during the heating up of the piece for the previous experiment. These results are given in Table VI, and are shown graphically in Fig. 4.

TABLE VI.

Optical Pyrometer Sighted on "Natural" Oxide Surface.

Temperature with Gas on.	Temperature with Gas off.		Difference.
° C.	° C.		° C.
750	694		56
	680	All flame off.	70
762	723		39
	718	All flame off.	44
780	747		33
	746	All flame off.	34
830	817		13
870	862		8

They show that even with the natural oxide the reflection effect is almost as great as in the case of the compact oxide, in spite of the different physical appearance. It is seen that the effect is exceedingly marked at temperatures below 800° C. Several readings are shown which were

taken with the whole of the gas off, and it is seen that whereas the removal of the remainder of the flame makes a large difference at lower temperatures, its effect is negligible at temperatures above 780° C. (Note. —The gas was shut off momentarily, and no fall in temperature was caused thereby.)

Comparison between Siemens Water Pot and Optical Pyrometer.

It would be difficult to imagine two instruments used for measuring the same function differing more in principle than these two.

Since, however, the water pot is used extensively in some works, it is necessary to see what degree of accuracy is attainable under the normal working conditions. To this end a number of comparisons were made, the ordinary " tester " taking the temperature by the Siemens ball, and the writer taking readings with the optical.

The following is a typical series of the results obtained :—

TABLE VII.

Optical.	Siemens Ball.		Difference.
° C.	° F.	° C.	° C.
900	1,620	882	−18
890	1,640	893	+ 3
850 / 845 } 847	1,500	815	−32
850 / 845 } 847	1,550	843	− 4

With regard to the third result in Table VII, it was noticed that the " tester " was very careless—in fact, whenever the discrepancy occurred it could always be put down to the same cause. The " tester " being warned of this, the following set of readings was obtained :—

TABLE VIII.

Optical.	Siemens Ball.		Difference.
° C.	° F.	° C.	° C.
880	1,590	866	−14
830	1,510	820	−10
860	1,565	850	−10
860	1,580	860	0

NOTE.—All readings taken whilst metal in the furnace.

Hence it appears to be possible to obtain sufficiently accurate readings (for commercial purposes) with the Siemens water pyrometer, provided that care is taken. That is to say, the method becomes unreliable owing to the large personal factor introduced.

Summary.

1. The various conditions of use of an optical pyrometer in taking the temperatures of liquid steel in the open have been compared with the calibration conditions, and have been shown to differ widely from them.

2. The errors due to the deviations considered in (1) have been shown to fall into two classes according to whether they were or were not accurately determinable. To the first class belong errors due to emissivity and polarization of the emitted light. To the second class belong such as are due to lack of monochromatism of the absorbing screen (absent in such types as the Wanner), to fumes, to light reflected from external sources, and to smallness of the source of light.

3. Several technical defects of the Cambridge optical pyrometer have been considered.

4. A suggestion has been made that in order to obtain *control* of the steel-making process pyrometrically, a refractory tube should be inserted into the bath when it is required to take the temperatures. A true black body condition would then be very nearly approached.

5. The use of optical pyrometry in the heat treatment of iron and steel is next dealt with. It is shown that the scale on billets (formed during reheating) causes difficulties :

(*a*) Inside the furnace at temperatures below 800 to 900° C., due to light reflected from the flames.

(*b*) Outside the furnace owing to its low thermal conductivity.

6. A comparison made between the Cambridge optical and the Siemens water pyrometer under normal working conditions has shown that although the latter is capable of an accuracy of 10° C., it is unreliable owing to the large personal factor involved.

TEMPERATURE DETERMINATIONS OF LIQUID STEEL.

Dr. A. McCance (Glasgow) also spoke on "Temperature Determinations of Liquid Steel."

Towards the latter end of 1913 experiments were carried out to find if any assistance could be obtained by controlling the temperature in an open hearth furnace by the use of an optical pyrometer. The work was done at the Parkhead steel works of Messrs. W. Beardmore and Co. with the co-operation of Mr. Service, and I wish to give to-night some of the difficulties which we came up against before a system was finally evolved, a system which is at present in use and by which some 10,000 to 12,000 determinations of temperature are made in a year for the purpose of controlling and recording heats of liquid steel.

The type of instrument employed was the Siemens optical, where a carbon filament is heated by a current until its colour is the same as the object on which the pyrometer is focused. With the usage the instrument got it was difficult to keep the milliampere meter constant and it required standardizing frequently. The lamps are supplied with a certificate stating the current necessary for different temperatures, and it has been found that the values given with a pre-war German standard are about 20° higher than the National Physical standard when tested against a heated black body under laboratory conditions. In any type of optical instrument it is of the utmost importance that the wave length of the light used for comparison should be standardized. For instance, I have tested a heated object using different screens and found the following great differences:—

	° C.
Thermocouple	1,188
Siemens optical	1,186
Using Wratten L screen	1,133
„ „ Hg „	920
„ „ blue „	750

The wave-length employed in the Siemens is supposed to be ·65 μ, but I have not measured this in the instruments which are used. This matter is important, and I wish to draw attention to the fact that every detail of a pyrometer should be standardized if concordant results are to be obtained, and in sending out instruments the greatest care is required to make sure that they are comparable. For instance, I recently received three new instruments and before putting them into use I tested them under black-body conditions, with the result that readings on the same enclosure gave values which were correct, 15° low and 20° low respectively against a thermocouple. These were supplied with a certificate stating that they were "correct."

Turning to the determination of temperature inside an open-hearth furnace, the apparent temperature recorded by means of an optical

pyrometer will be the true temperature *plus* an amount which will depend on the temperature of the flame and the reflective emissivity of the slag surface. As it was not advisable to shut off the furnace every time a temperature determination was taken, it was ultimately decided after experiments that the best places to focus the instrument on were the slag surface opposite the port that the gas was entering and the furnace roof immediately above this. At first wide variations were found in the temperatures recorded of as much as from 1,550 to 1,700 and over. The furnaceman was controlling the temperature by means of eye observations —not only by colour, of course, but by the many other indications known to the experienced melter, such as the condition of the brickwork, the fluidity of the slag and the appearance of the surface bubbles as well as by other "infallible" means which are the secret of the art. Towards the end of the operation when the slag is thickening up seemed to be the time when there was the greatest tendency to put more heat into the furnace than the brickwork could stand and which considerably shortened its life. Ultimately it was found that the temperature could be kept by means of temperature observations between fairly close limits running from about 1,630 to 1,650 apparent temperature, with advantage to the life of the linings.

Taking the temperature of the metal running out of the furnace care is necessary that no smoke comes between the metal and the heat-taker, who should always stand on the windward side of the stream. The composition of the metal alters the apparent temperature when carbon, manganese, or chromium are present, probably by altering the emissivity. The diameter of the stream also has an influence, but it is generally within the experimental errors of the method, as are also the differences in different parts of the same stream mentioned by Mr. Johns. For practical purposes an accuracy of plus or minus 5 degrees is all that is required, and this can be obtained if the instruments are properly looked after and they are in the hands of men who are experienced in taking temperatures under shop conditions. An average apparent temperature for liquid steel is 1,500, which, assuming Burgess' value for the emissivity of iron ·40, gives a true temperature of about 1,630°, and I consider that casting temperatures below this figure are cold heats.

Although taking the furnace temperature seems to ensure that all casts will have the same degree of heat, the problem is by no means so simple as it appears, because there are other factors which enter into the question and which are even of greater importance than the surface temperature. There is the amount of heat which is carried forward in the bottom of the furnace from the previous charge, and which is difficult to determine by simple means. The temperature of the bottom just before the charge is put in is really no indication, owing to the surface being so easily chilled by cold air from the doors and also having been made up by cold material. Again the rate at which the charge has been melted down and the rate at which the bath boils all go to determine the amount of heat which is put into the charge, and these are problems not yet quantitatively solved. But they are being attacked, and it is hoped that they too will yield their solution.

DISCUSSION.

At this point the **Chairman** invited general discussion on the above group of papers.

The Chairman: Had this discussion taken place two years ago, I know whom I should certainly have asked to open it. Dr. Harker has for the last two years been giving his attention to other matters, but I am sure he will retain sufficient interest in the subject of temperature measurement to oblige me by saying something now, especially on the theoretical side of some of the matters that have been mentioned.

Dr. J. A. Harker, F.R.S.: You, sir, have exactly described my position in saying that I have been occupied practically exclusively with other matters, and I came to this discussion to-night intending to have a complete change from my present interests. I regarded myself solely as a visitor and for that reason deliberately did not put my name down as having anything to say, as I have not been thinking about pyrometers for more than a year past. There are one or two matters, however, to which I have listened with very great interest and upon which, now I have been called upon, I should like to say a few words. With regard to the point raised by the last speaker, the people who have been making pyrometers in this country have not by any means neglected the matter; Mr. Whipple will bear me out in this opinion, and there are other makers present who know it quite well. This question of the glass for the eye-pieces is a very important matter indeed in discussing the divergencies from true temperatures obtained with optical pyrometers, particularly on the higher ranges, though it may be useful to point out that at quite low temperatures such as 700°, it makes little or no difference if the red glass be removed altogether. The Cambridge Scientific Instrument Company and a number of other makers, Messrs. Siemens among them, have, I know, devoted considerable trouble to obtaining the right quality of red glass, and in my view the implied slur on the British instrument-maker is undeserved. There are very great differences in the behaviour of different kinds of red glass and even between different samples of what is supposed to be the same glass. Some specimens transmit only a fairly narrow and well-defined band of the spectrum, while others allow transmission through a large range of wave-length. A simple test for identification of a bad quality "copper-ruby" glass is to observe whether there is any transmission of the sodium D lines. If this is the case, matching at high ranges will probably be difficult. The centre of gravity of the wave-length in which the pyrometer is working is quite troublesome to determine; it is important to know whether the dominant wave-length is, say, ·65 or ·70 μ so that the "black-body" correction may be properly calculated. The proper determination of this correction is one of the most awkward things in the whole process of getting true temperatures from readings obtained with a *commercial* optical pyrometer, as distinct from the more refined *laboratory* type. It is, however, not being lost sight of.

There is also another matter which may go a long way toward explaining some of the divergencies which have been spoken of to-night. It is very difficult indeed to make an optical pyrometer which will give readings absolutely independent of the size and distance of the object on which it is focused. In the total-radiation pyrometer there is, with

certain types, a small but perfectly definite variation both with size and with distance which is just as inherent in the instrument as coma or spherical aberration in a lens. The same effect is also found to some degree with most commercial optical pyrometers, especially those of the polarizing type, in which the optical arrangements have been so modified as to render the instrument usable over very low ranges, say from less than 700° upwards. You can partly get rid of it if you have a relatively big object. It is, however, a difficult thing to standardize an instrument on a small object and then to get the same reading up to perhaps 2,000° C. when the object is large, like a mass of steel in a ladle. This variation of reading with size of object is of course quite apart from the "black-body" question, and is a difficulty which is perhaps not very obvious to people who have not carried out pyrometer standardization, but is a serious one to those who have to imitate in the standardizing laboratory the conditions which obtain in a works. We have not 20 tons or even one ton of molten steel available at the N.P.L. on which to test pyrometers, which you asked Sir Richard Glazebrook to standardize for a fee of 30s. or so. The radiation furnace which serves as the hot object has generally to be of relatively modest dimensions. I think, however, that it is due to the N.P.L. to state that with optical pyrometers every instrument is actually tested right up to the higher ranges, and in those with two scales the upper scale is a *determined* and not merely a *calculated* one as is the practice at the Reichsanstalt.

One speaker asked for the standardization of optical pyrometers to be such as would enable temperatures to be determined within 3° at 1,500° C. In my opinion, while I do not deny that with carefully trained observers means of groups of observations may, under favourable circumstances, have a *relative* accuracy of this order, it would be quite futile to attempt to give corrections to nearer than perhaps 10° unless a number of other conditions were clearly defined. When the National Physical Laboratory took up the question of the standardization of the high-range pyrometers of all kinds some 15 years ago, one of the first things which came up was that steel-makers of the most progressive type were employing temperature-scales, which differed according to the particular fixed-points taken, by more than 50° at 1,000° C., and most attempts at measurement of higher temperatures were wild extrapolations. The melting-point of common salt could be taken from current books of tables at anything from 740° to 820° C. To-night we have steel-makers grumbling that the absolute accuracy of their works instruments cannot be guaranteed to 3° C. I think, sir, that shows things have "moved" in the meantime to an extent which few people would realize.

Dr. A. McCance: I did not intend to cast any slur on the manufacturers. I was simply mentioning one or two difficulties that I have been up against during the last three or four years due to the instruments used, and I am glad to have Dr. Harker's assurance that the matter is being investigated.

M. Le Chatelier, writing after the meeting, was glad to see Mr. Cosmo Johns recommend the use of optical pyrometers in metallurgical works. The reasons why they had not been greatly used up to the present were not so much on account of any difficulties or sources of error inherent in such instruments, but because few engineers having had occasion to make photometric measurements they regarded such measurements as difficult and preferred direct-reading apparatus. Optical methods, however, involved less serious errors than electrical methods of measuring high temperatures. Thermoelectric couples were of great service in the laboratory in the hands

of observers familiar with their use. But in the works they easily got out of order, and even skilled observers would allow considerable errors to pass unperceived. Total radiation pyrometers, which received the heat rays on a small thermoelectric junction, were even more dangerous on account of the difficulty of maintaining at a constant temperature the cold junction made by the case of the apparatus.

On the other hand, optical pyrometry depending on monochromatic radiation was subject to no such important errors provided a flame and not an electric lamp was used as the standard. In the hands of almost any operator it would yield almost exact results, the accuracy of which would only vary a little with the experience of the operator. The use of this method necessitated, it was true, a correction on account of differences in emissivity between one body and another, if absolute measurements were required; but in industry the essential purpose of pyrometric measurements was to ensure constancy of temperature in a series of successive operations. Incandescent bodies would always retain the same emissivity, and ignorance of its magnitude would not in any way interfere with the value of comparative measurements.

Mr. Cosmo Johns in his study has otherwise made all the corrections necessitated by the low emissivity of steel. He has perhaps taken unnecessary precautions in extending them to measurements made in the interior of a furnace. If the temperature there was absolutely uniform there would be no necessity to allow for emissivity at all; every point in the enclosure would radiate like a "black body," that is to say, would have an emissivity equal to unity. In reality there were small differences of temperature between one point and another necessitating a small correction impossible otherwise to determine. In approximating to 25° only instead of 100° or more one came very near the truth. In this manner one arrived at a temperature of 1,700° for the hottest part of a steel furnace. This temperature could hardly be exceeded, since silica bricks softened at about 1,750°. It was difficult to admit that the surface of the bath heated principally by radiation from the roof could attain a temperature higher than this latter figure.

Mr. S. A. Main, B.Sc. (Sheffield) (*partly communicated*): I think the Faraday Society is to be congratulated on the success of this meeting, as shown by the excellent set of papers it has brought forth, the number of exhibits, large attendance, and vigorous discussion. It is apparent that even more time might profitably have been devoted to the meeting. The last occasion on which a Symposium on Pyrometers took place was as long ago as 1904, under the auspices of the Iron and Steel Institute, through the instrumentality of Dr. Stead, Sir Robert Hadfield, and the late Mr. Brough. The subject has since been discussed in a rather fragmentary manner in individual papers, but the progress made is rendered strikingly apparent by the papers presented to this meeting. In this progress British instrument-makers have taken a large share, having spared no efforts in ascertaining the conditions under which pyrometers are employed and the various features influencing their accuracy. The success of Mr. Whipple and the Cambridge Scientific Instrument Company in producing an optical pyrometer which replaces, and in some respects improves upon, the German instruments, should be recorded. A large amount of work has to be done under the control of optical pyrometers, and serious difficulties would have arisen in connection with the output of munitions if this instrument had not been forthcoming.

The following remarks, which are based on several years' experience

with pyrometers in the works of Hadfields, Ltd., Sheffield, may be of interest:—

Pyrometers in General.—Various speakers have pointed out the necessity for considerable intelligence in the use of pyrometers. I think this point cannot be too strongly emphasized. A pyrometer is not, for example, like an ammeter or voltmeter, which, if made by a reliable firm, may be used with little expert knowledge to obtain accurate readings, and with little attention to the instrument itself. A pyrometer may vary, not only in itself, but according to the manner of usage. It requires constant supervision. An ordinary workman may be trained to use and take readings with the instrument, according to specific instructions, but the care and responsibility must be placed in the hands of one of the staff, with a proper knowledge of the principles involved. In other words, it is not sufficient merely to buy a pyrometer, but also to have an acquaintance with the science of pyrometry. With knowledge of the principles, the most suitable pyrometer may be chosen, kept in calibration, and applied in the proper manner to obtain accurate results.

Thermoelectric Pyrometers.—The question of a satisfactory base-metal couple still remains to be solved. While it is quite true there are a good many base-metal couples on the market which are suited for the comparatively low temperatures up to 800° and 900° C., for temperatures above 1,000° C. there is still nothing to compare with Le Chatelier's original platinum and platinum-rhodium element. While supplies of these metals are available, there is nothing serious about this: even at present prices this couple pays for itself in the regularity of the heat-treated products. The fact is, however, that platinum is becoming more and more scarce, the price continually rises, and it is within the bounds of possibility that there may not be enough of these metals available for pyrometry—a serious prospect, having in view the large amounts which are being used for this purpose. Dr. Burgess, of the Bureau of Standards, has told me that base-metal couples are being successfully applied in America, but this being the case I do not think the same accuracy can be looked for, or obtained, in American works as in this country.

There are a number of quite excellent pyrometers on the market described as portable pyrometers. My advice with regard to these instruments is, take as little advantage of their portability as possible; have an instrument for each furnace or group of furnaces. Moving these delicate instruments about the works, to say the least, does them no good, and, further, the calibration varies with the surroundings and the levelling.

Optical and Radiation Pyrometers.—Our experience with radiation pyrometers has not been particularly favourable to their use, largely, perhaps, due to the conditions in a steel works being hardly suitable for their employment. There is a certain inherent time-lag in taking readings. It is true this may be minimized by proper manipulation, but, as a previous speaker has pointed out, the conditions are often such that only a matter of two or three seconds is available for the reading. Another trouble we have found is due to the unequal heating of the instrument itself by radiation from the furnace, which affects the zero. This type of instrument has, however, the advantage of being direct-reading, that is, it does not require setting by the operator for each reading.

As between the two principal types of optical pyrometer, namely, the polarizing type, represented by the Wanner, Leskole, and Cam-

bridge Scientific Instrument Company's instruments, and the disappearing filament type, we have tried these side by side, and our experience is in favour of the former. With the same amount of care both types of instrument give equally accurate results. The polarizing type, however, has no inherent lag, a reading being obtained as soon as the operator can make the adjustment. The disappearing filament type requires a certain interval of time for the lamp filament to acquire the temperature corresponding to the current which is put through. The polarizing type also has the great advantage of possessing a definite physical law, which may be expressed mathematically. This facilitates and checks the calibration, especially if one of the calibration charts shown among the exhibits of Messrs. Hadfield (see p. 158) is made use of. A resulting advantage is, the extrapolation to higher temperatures is more accurately carried out by following the same law.

The following figures regarding the wave-length of the coloured glass used in optical pyrometers may be interesting, as supplementing those given by Mr. Griffiths. The figures have been obtained by calculation from the calibration curves of a number of instruments. The average of a number of instruments made by the Cambridge Scientific Instrument Company is ·650 μ, with a mean variation of $\pm$·009. The average of the German-made Leskole instrument is ·653 μ, with a mean variation of $\pm$·0075. These figures show that the glass used in the English instruments is of the same average colour as that in the German instruments, but is rather more variable.

The principal trouble experienced, however, is in connection with the "neutral" glass which is interposed for the higher temperature measurements, such as those on molten steels. This glass we have found very much increases the effective wave-length, the average of several instruments made by the Cambridge Scientific Instrument Company with the neutral glass interposed being ·689 μ, with also a mean variation of $\pm$·025. Not only, therefore, is the glass not so neutral as required, but it has also shown considerable variation. As the question of emissivity corrections is mostly connected with these higher temperatures, this is a point which should be seen to. One or two instruments show a satisfactory wave-length both for the low-reading scale and also for the high-temperature scale with the neutral glass interposed. We have found in some instruments a departure at the lower ends of the scale from the proper law, the angular motion of the analyser for a given temperature being lower than indicated by the law, the remainder of the scale being quite satisfactory.

I should like to point out that there is need for a good recording optical pyrometer. Such instruments, of the radiation type, are already available, but, as mentioned above, these do not, in their present form, quite meet the conditions in a steelworks.

Brown Control Pyrometer.—It may be interesting to members to have the results of our experience with this apparatus, shown among the exhibits, which we believe to be the only one in this country. The electrical arrangements we have found to work very well—that is, the instrument quite reliably actuates the main switch controlling the current, according as the pyrometer is reading above or below the control temperature. We have found some difficulty, however, owing to the fact that the thermocouple is of base metal, and rather heavily lagged, so that the furnace itself may fluctuate in temperature between fairly wide limits without producing corresponding fluctuations in the temperature of the couple itself, which latter, of course, is what actuates

the control pyrometer. If a similar pyrometer could be devised, but making use of a platinum-platinum-rhodium couple, the latter having less heat capacity and requiring less protection, improved results would be obtained. This point would apply, however, to a less extent with larger furnaces, where the couple is better able to follow the more sluggish temperature changes of the furnace.

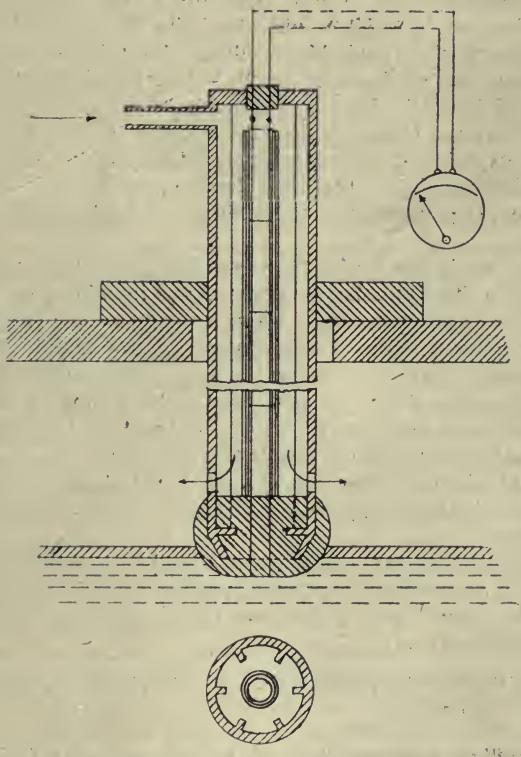
Mr. John Rhodin: With regard to optical instruments which are dependent upon colour, they are so subject to the personal equation that I do not think the optical comparison of temperatures will ever replace the radiation type or the thermocouple. We have an example before us. I remember before the penumbral apparatus was brought out that when adjusting the polarimeter the variations covered 15 deg., and now the penumbral instrument has practically replaced all the original polarimeters which depended upon specific colour. Hence, to call an optical pyrometer an instrument for measuring temperature I do not think is quite correct, because, after all, the intensity of the temperature is actually the radiation, and the temperature is the fourth power of the radiation. We were unfortunate in beginning our temperature system at a time when physics was not so developed as it is now. We started with the expansion of mercury or water, but we found afterwards that this gave not an intensity scale but an energy quantity scale, and that the very latest development in pyrometers, the thermocouple, is independent of its dimensions and hence measures intensity. Our best way now would be to reason and go back to defining temperature as a function of the radiation; but that is a wider subject. I do not think the optical pyrometer is the thing.

Dr. F. Rogers (Sheffield) said he was not satisfied with radiation or optical pyrometers for work upon molten metals. He had for long sought to use thermocouples without success, but recently he had had success with the method which he described (see Fig., p. 115). The ends of the thermocouple wires have refractory material (clay or moulder's compo, etc.), moulded about them and firmly into contact with, and even over the end of, the sheath. The ends of the wires are not united to form a thermocouple, but they are placed in contact with the molten metal. A perfectly steady reading is instantly obtained, and in the majority of applications the pyrometer can then at once be withdrawn before the stem becomes heated sufficiently to damage it, although in actual tests of several minutes' duration the pyrometers had not failed. Merely the tip is heated to the temperature to be measured, and possibly the wires melt or alloy with the molten metal for a very short length, perhaps $\frac{1}{16}$-in. but the electric circuit remains continuous, and the net effect corresponds to what would be given by a thermocouple of the two wires simply, under otherwise similar conditions. When the stem of the pyrometer is exposed to flame, as in the open hearth furnace, it may be air cooled. The air enters the sheath near the head, and blows out through holes a little above the end. All trouble with the cold junction is very conveniently avoided in this type by simply placing the cold junction inside the sheath near the air blast inlet.

He had not yet made a thorough calibration of a pyrometer of this type, but gave the following examples of readings obtained in trials. In each case a galvanometer was used whose readings when used in the ordinary way with the thermocouple were approximately correct, and for the trial the resistance stated was used in series. In the final column is given the temperature calculated from the ratio of the resistances, but this does not give necessarily a very accurate idea of the temperature.

In each of these trials the end of the pyrometer was actually immersed in

No.	Trial.	Resistance of Galvanometer and Ordinary Thermocouple Circuit.	Additional Resistance in Series.	Steady Reading.	Temperature Calculated from Relative Resistance.
1	Solidification of cobalt-chrome high-speed steel, in crucible ...	132 ohms	100 ohms.	863	1,530
	Solidification of copper (in open furnace) ...	Ditto	Ditto	600	1,662
3	Temperature in 70-ton acid open hearth steel furnace, during melting down	54	24	850.	1,450



the molten metal for several minutes (3½ minutes in trial 3), as they were intended to be of the nature of endurance tests, *inter alia*. In trials 1 and 2, air cooling was not used. In trial 1 the wires were in one outer sheath; in trial 2 they were in two separate sheaths. In trial 3 the stem was air-cooled, and was about 9 ft. long, massive, and was clad with heavy clay sleeves.

He felt every confidence that they now had a really practical and sensitive method of obtaining the temperature of the molten metal, in the bath or in the crucible. This was essential for really complete control, for so

long as the temperature in making open hearth steel could only be effectually taken after tapping the furnace, practically they had burned their boats—there were very few means of control remaining at that late stage. This was particularly important, not only in regard to teeming temperature, but as regards "condition"—that was, deoxidation—of the metal. The first developments of the open-end couple were made in conjunction with Mr. P. R. Kuehnrich and Mr. J. F. Kayser in experiments in the crucible at the Spartan Steel Company's works, Sheffield. The experiments on the acid Siemens furnace were made at Messrs. Taylor Bros. & Co.'s Works, Leeds. He thanked both firms for permission to publish the respective results.

(*Communicated later :*) Although Mr. Darling's suggestion (see further, p. 144) did not go all the way, yet in one respect it resembled the pyrometer which he (Dr. Rogers) had described, in that the thermocouple metals were not directly joined to form a couple, and they might even be in the fused state. As it appeared to him, however, Mr. Darling's suggestion would not lessen the difficulties with sheaths, especially if one attempted to use it in molten ferrous metals, which would alloy with the graphite contact block, unless it were enclosed in a suitable sheathing ; but the point was that it would doubtless extend the usable range for given thermocouple metals, as in fact the method which he (Dr. Rogers) had described above had certainly done.

Mr. P. Peakman (Manchester) : Technically, accurate high temperature measurement experiments are exceedingly interesting and useful, but for the man in the shops, i.e. on the steel furnace, in the ironfoundry, or the hardening shop, they mean little or nothing, and hence their practical value is very small.

For all who are in touch with the works find such terms as "bright red" and "dazzling white," etc., in common use, and intelligent use, and the good results met with in practice almost warrant the disuse of pyrometric control.

However, my experience in temperature control, both in heat treatment shops and foundries, is that as long as the man on the furnace has some means of checking his judgment by eyesight, even without knowing the actual temperature of the work, that is all he needs, and this type of control lies easily within the reach or scope of the simple thermocouple.

For example, in the hardening of high-speed steel, the couple can be inserted into the bottom or side of the furnace, but not entering into the high temperature zone.

The actual furnace temperature is then found by means of salts or metals, or by means of an optical or radiation pyrometer ; the temperature of the couple is then noted, and checks are taken to correct periodically the temperature gradient, e.g. :

Actual Furnace Temperature.	Couple Temperature.
1,350° C.	920° C.

Even supposing, however, that one has no means of taking the actual temperature, after one or two hardening experiments, the best result for a certain steel are obtained, the couple temperature is then noted, and all the subsequent hardenings are made at this temperature, as shown by the couple.

By this means a recording instrument can be fitted, so that records of the running of the furnace can be made and kept for reference.

The weakness of this method is of course "time lag," but for all practical purposes this can be ignored, especially where the furnace is in use for long periods of time.

The great advantage of this method of control is that a permanent record can be made automatically for each furnace. It can be adapted to all classes of furnaces and ladles, etc.

At any rate, this method of control is better than that used in South Wales, where a board is painted a special tone of red, and when the furnace is the colour of the paint, then it is supposed to be correct; or even still better than using a particular tint of orange peel, for the best temperature at which certain components for cycles may be carburized.

For calibration of thermocouples I have found that an excellent method is to use a piece of steel of known carbon transformation point, for by this means there is no danger of interaction between the metal of the couple and the material in which it is placed for calibration. It is, however, important to drill a fresh hole for each calibration, otherwise the film of oxide may interfere with the test or change point, and entirely to prevent oxidation at temperatures of about 950° C. means a costly outfit.

Mr. C. J. Peddle (Derby) spoke on "Pyrometry as applied to the Manufacture of Glass."

It may be of interest to the meeting to have the experience of a worker in a sphere other than that of iron and steel. My field of labour lies in the manufacture of glass, in which industry pyrometry has been neglected in the past. Recently, however, the glass manufacturer has begun to appreciate the pyrometer and value it at its true worth.

In glass manufacture it is necessary to control the temperature (1) of the furnace, (2) of the molten glass in the furnace, (3) of the annealing of the finished article. The control of the temperature of annealing is the simplest of these three problems, because it is a low temperature, probably never more than 500° C., which is being dealt with. This can be accomplished quite satisfactorily by means of base-metal thermocouples placed in the annealing chamber and reading automatically or at sight on a recorder.

The control of furnace temperature is a somewhat difficult problem in our industry, particularly where glass is melted in tanks or open pots. Although the furnace temperatures are considerably less than those in the iron and steel industry, being some 400° C. lower, yet the atmosphere of the furnace, where the glass is in actual contact with the furnace gases, is such that any thermocouple inserted through the roof or sides of the furnace has, as a rule, a very short life. The envelope of the couple is rapidly attacked, and the couple itself soon deteriorates. Where closed melting-pots are used, and vapours from the glass do not actually pass into the furnace, the thermocouple has a longer life and is more satisfactory.

More important than the furnace temperature is the actual temperature of the molten glass, and here the problem is widely different from that of the iron and steel industry. Direct insertion pyrometers are useless, owing to the attack of the molten glass on the envelope of the thermocouple. A fireclay envelope would quickly dissolve, and a metal envelope would tend to discolour the glass. Recourse therefore must be had to either the radiation or optical type of pyrometer. The former has the advantage in so far as it may be made automatically recording, but since this is not necessary when taking actual glass temperatures, and indeed cannot be done except over the short interval of time the glass surface is exposed for working, there seems little to choose as to the availability of the two types. My own personal preference is for an optical pyrometer of the Cambridge type. In a glass-pot there are almost ideal conditions for working an optical pyrometer. The

whole of the glass is enclosed except at the small sighting opening, and so an almost complete "black body" condition exists. To my mind it is a proof of the accuracy of a pyrometer when known glass conditions result at different times with the pyrometer registering the same temperature. An optical pyrometer responds to this test quite faithfully.

Radiation pyrometers of the Foster type tend to deteriorate badly after a comparatively short working life, due to the "peeling" of the mirror. This may be due to the somewhat rough usage so hard to eliminate from works practice.

Professor Arnold's remarks on the Mesuré and Nouel pyrometer were very interesting to me, because I have had considerable experience of that extremely useful instrument. It is small and does not require "setting." I most heartily agree with Professor Arnold that the personal equation with this instrument is considerable. Only in the hands of an experienced worker is it reliable. In working the instrument the analyser is rotated until the "sensitive" or "midway between red and green" colour is obtained, and the angular rotation is read. This angular rotation is transformed into centigrade temperature, using Pouillet's scale. On this scale a rotation of 40° corresponds with 900° C., a rotation of 57° with 1,200°, and so on. In practice I find that different persons read a different "sensitive" colour when sighted on the same incandescent mass, and so Pouillet's scale is useless. To work the instrument properly each person using it must draw up his own scale of temperatures corresponding to different sensitive points, using a Cambridge optical pyrometer say, to standardize by. Then readings by two different observers will agree. As an example, I read 65° on the Mesuré and Nouel, and my colleague 67°; but our actual temperature record was the same, say 1,250° C., because my scale reading 65° is equivalent to 1,250° C., whilst in his scale 67° is its equivalent. One bad fault with the instrument is its tendency to read high when it gets warm.

Being in the glass industry, I was interested in what Dr. Harker and Dr. McCance said about glass for optical pyrometers. There appears to be a want of glass of definite refractive index for lenses, etc., and also a demand for red glass which will only pass monochromatic light. Probably if instrument makers would specify exactly the glasses they require, work could be done and the glasses discovered. One melting would supply glass enough to last the optical pyrometer manufacturer for a very long time.

Dr. Walter Rosenhain, F.R.S.: There is a great number of very interesting questions raised by these papers. Perhaps the most important thing that has been said to-night is one which has been a little neglected in the discussion, and that is the importance of not only obtaining a correct temperature, but of finding the temperature of the object wanted, and not of something else. The use of pyrometers is becoming fashionable at the present time. They are used extensively, and in many places they are employed in a manner which is worse than useless. It is absolutely necessary to realize that putting a pyrometer into a furnace will not necessarily give the temperature of the articles, metal or otherwise, which are heated in the furnace. Dr. Hatfield draws attention to this, and gives an example from the practice of his own works, which is typical of the best way, or one of the best ways, in which the thing can be done. One can carry it a step further still, and not only make a preliminary trial run in order to discover the rate at which a given mass in a furnace acquires heat, but one can actually in some cases introduce with the working charge a dummy article with a thermocouple in its interior. In the case of a charge of 20 or 30 small things, one or possibly two are put in with holes in them with thermocouples in the

holes. If the temperature of these couples is taken, that gives a result which is quite different from the ordinary temperature of the furnace. That is not everywhere possible, and consequently it is no doubt very desirable, as Dr. Hatfield mentioned, to be able to calculate from the known physical constants of the material the time it will take thoroughly to heat up a given mass, but I am afraid there are difficulties in the way. There are a good many factors, some of which Dr. Hatfield mentions himself; but so far as the thermal conductivity is concerned I warn him that it is not sufficient even approximately to take the thermal conductivity of the metal at the ordinary temperature from 100° down to 0°, but that it is necessary to determine the thermal conductivity and the specific heats also at the high temperatures involved in the work. At Teddington we have come across the problem in quite a different connection in regard to aluminium alloys, and my colleague, Dr. Griffiths, has developed a method of determining the thermal conductivities at temperatures up to 900° C., and he could possibly go to considerably higher temperatures. With regard to conductivities, I am not surprised that Dr. Hatfield has found large differences in thermal conductivities between various alloy steels. Sir Robert Hadfield has mentioned that manganese in steels acts as a bad thermal conductor. Curiously enough manganese carries that property into other alloys. One per cent. of manganese produces a large effect in depressing the thermal conductivity of several alloys. Nickel is not so bad, although with 25 per cent. the thermal conductivity of nickel steel is very much lowered; but it is evident that these differences are large and will have to be considered in the treatment of alloy steels.

With regard to the question of pyrometry of non-ferrous metals by means of optical instruments, I would raise the point that although the figures Professor Donnan has given are very interesting, their interest is, perhaps, more theoretical than practical. Any one who has used both types of instrument, however, in this connection will think that the thermocouple is the more useful. Dr. Rogers, in putting his platinum iridium wires in fireclay, or some other substance, is not risking the wires but condemning them. These wires will not stand that treatment, and they will become seriously damaged by silicon and be very rapidly destroyed. The saving grace of the method is that the exposure is only for a few minutes, but I am quite sure that the consumption of platinum wire by that method will be extremely large, and the risks of error also very large indeed. I think the future, after all, with these very high temperatures must lie with some form of pyrometer the sensitive members of which are outside the furnace. If you have to put things into the furnace at the temperatures of melting steel, I am inclined to think that their life must be short, although it may be merry.

Dr. F. Rogers later wrote that Dr. Rosenhain's criticism was not found to apply materially in the actual and reasonable use of the pyrometers. Probably Dr. Rosenhain was under the misconception that the pyrometers must be immersed for a long time in the molten metal, which was generally not the case. The plan of the trials recorded included the fairly long immersion in order to test the durability and reliability of the pyrometers, and he would emphasize the fact that in practice in the majority of cases it was sufficient to immerse the tip of the pyrometer for from 2 to 10 seconds only at a time. There was no lag with the naked wires in contact with the molten metal. It was possible to grind a layer off the tip of the pyrometer if ever one felt a doubt that it had been affected by use, and so get back to fresh material in a moment. He would repeat that this had already proved a valuable practical method, although its exact standardization yet remained

to be carried out, and he hoped that the N.P.L. might have the means of co-operating in that aspect of its development.

Mr. Walter Carter: I think that pyrometers are generally sold too cheaply, with the result that the maker is not able to give the assistance to the user that is sometimes necessary.

It cannot be expected that all users of pyrometers can be well acquainted with the upkeep of these instruments, and if the margin of profit were greater, it would then be possible for pyrometer makers to enable their representatives to pay more frequent visits to users.

One of the undesirable features of many pyrometers is that they are not made sufficiently robust. They are doubtless quite proper for laboratory use and practice, but in many cases are lacking in essential details and robustness for works practice.

It should not be overlooked that pyrometers are frequently used under dirty and other arduous conditions. It is also difficult at times and under certain conditions to read the scales, and it might be worth while considering an attachment to a pyrometer which would enable the dial to be easily and continuously illuminated from a source of light not visible to the operator. This would not be a difficult matter should a pyrometer maker really give his mind to the problem.

The next point is that there is room for two totally different kinds of pyrometers. For many purposes it does not matter how much a pyrometer may be registering incorrectly so long as it is permanent and not variable in its readings, and as to whether it is 20° or 50° wrong is really of no practical moment. The essential feature of a pyrometer of this kind is that it must not vary. The views of the pyrometer makers as to whether this feature is possible would be much appreciated.

I realize, of course, that for other purposes it is necessary to have a pyrometer registering as accurately as possible, as such pyrometers can be calibrated regularly. It is not, however, always possible or even sometimes desirable to have pyrometers registering accurately, but, to repeat, it is very desirable that such pyrometers shall be very constant.

The **Chairman** thought the meeting would like to hear the point of view of the pyrometer maker on some of the criticisms that had been made by Mr. Carter and others. He asked Mr. Whipple to reply briefly.

Mr. R. S. Whipple: About three months ago I spent a pleasant afternoon with Mr. Carter going through his hardening shop and other works, and in a very friendly way he offered suggestions for making pyrometers more suitable for the rough treatment meted out to some of them in practice. We are trying to take advantage of that advice.

I do not think the users of pyrometers realize all the difficulties of the pyrometer maker. In some cases he is asked to make the scale on which the instrument reads as open as possible, and to obtain this result a sensitive instrument has to be constructed, and this, unless very special precautions are taken, involves difficulties with the stability of the zero, creep, etc. The majority of users do not realize how much the accuracy of their work depends upon the position in which the pyrometer is placed in the furnace. I remember very well going into a large works in Birmingham where complaints were made that the instruments were not reading as high as they should have done. I examined one of the pyrometers and found that it was mounted through the

top of the furnace, the head being practically on the top of the brickwork. I suggested that it would be advisable to place the pyrometer horizontally, and the result was that the apparent temperature on the indicator rose by 100° C. It was obvious that when the pyrometer was mounted vertically the cold junction was roughly 100° hotter than in the horizontal position.

In the majority of cases sufficient care is not taken in selecting the position in which the pyrometer should be placed in the furnace. Pyrometers are generally broken mechanically and are not burnt out.

With regard to the optical pyrometer, I think it must be admitted that the subject has advanced a great deal during the last few years when a gentleman of Mr. Cosmo Johns' position can demand an accuracy of 2° when working at 1,500° C. He would not do this if it were not for the fact that he believes it may be possible to obtain the desired accuracy.*

The Cambridge optical pyrometer is, after all, the old Abney colour box as modified by Koenig and improved by Wanner, and is capable of work of high precision.

The question arose as to whether it would be an improvement to fit a vernier to the temperature scale on the instrument so that the scale could be subdivided. After consideration we came to the conclusion that no higher accuracy would be obtained if such a vernier were fitted. With a little practice one can subdivide a division such as a millimetre to an accuracy of $\frac{1}{10}$th mm. with precision, and a vernier in such a case appears to be an unnecessary complication.

As Dr. Harker stated, the obtaining of monochromatic red glass has been a great difficulty. The glass we are now using is supplied by the Corning Glass Company of Rochester, New York. This firm has devoted a great deal of time to the production of monochromatic glasses.

I think that in future we shall have to ask Sir Richard Glazebrook to add a statement on his certificates of test as to the limits of wave lengths of the light passed by the coloured glass on the instruments. This could readily be determined for every pyrometer, and would, I believe, add considerably to the value of the standardization.

Mr. C. R. Darling (*communicated*): Dr. Hatfield in his Paper draws attention to the important practical problem of the heating of masses of steel in furnaces in relation to the time required for heat to penetrate to the interior. Some figures bearing on this question were first published in my book, *Heat for Engineers*, 1st edition, 1908, and refer to mild steel billets of circular section. The results were obtained by inserting a thermal couple in the centre of the mass, and noting the time required for the centre to attain 1,900° F., the temperature of the furnace being maintained at approximately 2,000° F. The diameters of the billets ranged from 18 in. to 45 in., and the time required from 3¼ hours in the first case to 19½ hours in the last. An examination of the figures shows that the time required varied nearly as the square of the diameter; that is, directly as the area of section. Experiments of this kind on test ingots, of the same dimensions and composition as those operated on in practice, would furnish the necessary data in all cases, and a reliable set of figures relating to various sizes and shapes of different kinds of steel would be of great value. Such figures would be far more reliable than those

* *Note added December 5th.*—In the present state of our knowledge it is admittedly impossible for any one to measure a temperature of 1,500° C. by an optical pyrometer to an accuracy of 2°. The gas scale temperatures are not known to this accuracy at this temperature, and the black body conditions under which any observation of such temperatures is being made must be considered most carefully. Given satisfactory black body conditions it may perhaps be possible to measure a temperature of 1,500° C. to an accuracy of ± 5° C.

deduced from determinations of conductivity and specific heat, both of which, as Dr. Hatfield points out, vary to such an extent with the temperature as to render calculations uncertain. With reference to Dr. Northrup's pyrometer based on the expansion of molten tin, it may be mentioned that Dufour, in 1900, suggested molten tin in a quartz envelope for measuring high temperatures. The objection to this in practice would be the devitrification which quartz undergoes at elevated temperatures, and the graphite enclosure used by Dr. Northrup would appear to give promise of a serviceable instrument. In some recent experiments in which artificial graphite was used, I found that prolonged heating rendered the graphite very friable; and if this be a general property of graphite, Dr. Northrup's instrument would require careful handling. Possibly, however, the graphite I have used has not been of the best type.

Mr. W. J. Rees (*communicated*): A lengthy experience of the use of radiation pyrometers of the Féry type in a glassworks has shown the absolute necessity for protecting the mirror from the tarnishing action of sulphurous gases, more particularly when the instrument used is in proximity to a glass furnace melting a salt-cake batch. Very slight tarnishing causes the reading to be appreciably low. The best protection is afforded by fitting a thin plate-glass window to the Féry telescope; the instrument then needs calibrating with this in place. The earlier type of Féry telescope, in which a quartz or fluorite lens was used instead of a plated concave mirror to focus the radiation on the thermopile, had advantages for works use, as it was completely enclosed.

The Wanner optical pyrometer was also found of great value after an observer had obtained sufficient experience in its use. The observations of a trained observer were dependable within $\pm$ 5° C. at temperatures from 1,100° to 1,300° C.

Reference was made to the difficulty of obtaining in this country monochromatic ruby glass for use with optical pyrometers of the Cambridge type. Tentative experiments have shown that there is no insuperable difficulty in the manufacture of this ruby glass, in which colloidal copper is the colouring ingredient, and as the required quantities are so small, manufacture on the laboratory scale would probably be sufficient. It is obviously desirable that the monochromatic glass should be made in this country, and it is to be hoped that one of the glass research laboratories will produce the necessary supply. A paper on "The Effective Wave-length of Transmission of Red Pyrometer Glasses" * was read before the American Physical Society in April, 1915, by Messrs. Hyde, Cady, and Forsythe, of the Vela Research Laboratory, and reference is made to the use of Jena "Kupferrubin" glass, No. F. 2745, and Jena "Rotfieter," No. F. 4512. Waidner and Burgess, Priano, and others had recognized that, owing to the breadth of the transmission band, the effective wave-length of monochromatic light is subject to change with change in spectral distribution of the incident radiation, as occasioned by changes in temperature of the radiating source, and the authors determined the effective wave-length between two definite temperatures of a black body and the change in this effective wave-length with changes in the temperature interval.

Mr. Alleyne Reynolds (Hove) (*communicated*): It is now twenty years since I have had daily to measure temperatures reliably and quickly when hardening fire tubes, armour plates, etc., and I was much disappointed at the absence of any practical advance indicated in regard to enabling the

* The *Physical Review*, vi. 1, July, 1915.

heat treatment of large thin forgings to be better conducted. I will go further and even say that my general impression is that a pyrometer, as apparently generally employed or even capable of employment, is from the manufacturer's point of view about as dangerous a weapon as an automatic pistol in the hands of a schoolboy. There was no attempt at any specification of demands to be fulfilled by a pyrometer or of precautions required to be observed in using one.

I only found two pyrometers of any real use in the "nineties," viz. the Mesuré and Nouel optical pyrometer and a piece of fairly dry pine lath. I had started elaborating others when I ceased to require them, owing to change in my occupations. All attempts to employ refined pyrometers for deciding the moment when to quench large forgings must result in greater error than that of a practised eye, unless quick and reliable readings are securable. So far back as over twenty years, aided by a grand crane and simple tackling and other devices of my own, I thought nothing of cutting down the time from full heating of the forging to its immersion in the oil tank to occupy only five minutes. That is to say a large "A" tube 40 to 50 feet long was so handled that pyrometer readings top, bottom, and middle were taken, it was attached to the crane, lifed out of the furnace and fully immersed in the quenching tank within five minutes of first interfering with its heating. This depended on simple but good devices being employed. The lifting tackle seized the tube safely without exercising side pressure on it, and in spite of pendulum swing engaged it quickly and safely.

Pyrometer readings were taken through a 2-in. gas pipe passed through sight holes up to the surface of the forging, and the flame could be cut off and restored full bore in one second of time. I should now employ more refined gas-valve operating devices, and the inspiration for these may be taken from many old devices for operating the reversing gear of locomotives. An excellent device for the purpose would be one I saw over twenty-five years ago on some North-Eastern locomotives. This was a combined screw and hand lever reversing device. The pawl on the hand lever, in lieu of engaging in a sector plate, engaged in a coarse screw thread cut in a barrel of the same curvature as a sector plate would be. Thus the driver could extremely quickly release the pawl and let the engine into full gear, and equally quickly pull the lever back and let the pawl fall into the same portion of groove as it had been when finely adjusted by means of using the screw to operate it.

I found that my assistants and myself varied hardly at all in our readings with the same or different Mesuré and Nouel pyrometers, but we found the scale furnished by the makers unreliable, our readings varying some 40° to 50° C. therefrom. Now, the proper quenching temperatures were ascertained by the laboratory staff using a refined thermocouple pyrometer for the purpose, and therefore, whether that were correct or not as to the actual temperatures, the important thing was to heat the forgings to the temperature which the laboratory pyrometer had demonstrated to be required. I therefore trained myself and my assistants in using simple pyrometers *to take reliable readings of the laboratory pyrometer.*

For this purpose I used a 2-in. gas pipe with a closed end immersed in a lead bath in which the end of the refined pyrometer was also immersed, and further, the reading of the latter was only able to be made in an ante-room, so that when making my readings I did not even know the electrical pyrometer readings. A system of signals was arranged, and I and my assistants and the laboratory staff took readings and noted them simul-

taneously, and only compared them when the tests were completed. By these means human errors and obsessions were reduced to a minimum.

Also, using a pipe of the same length and diameter as the closed-ended one for taking readings of the forgings, errors due to varying fields of vision were eliminated.

I found the optical pyrometer only reliable over a range of some 150° C., but repeated tests in varying states of health showed it reliable within that range.

For lower temperatures I found only one pyrometer reliable, and reliable to a most astonishing extent, that is to say, within 10° over a range of some 200° C. The pyrometer in question was a wooden lath some $\frac{3}{4}$-in. × $\frac{3}{8}$-in. section, cut to a knife edge. Differences of dryness had within reasonable limits very little effect. Varying degrees of fuming with or without friction, sparking, free sparking, flaming only when rubbed, just igniting, etc., gave a sensitive and reliable scale.

This was established on similar lines to the scaling of the optical pyrometer. A 2-in. diameter solid bar of iron was heated in the lead pot, and the laths were tested on this.

I had commenced investigations on various graduated wax, fusible metal and other bars pressed in contact by means of springs in tubes for a given unit of time, when, as before stated, I had to drop the work. I think something may be elaborated on these lines.

Using double tubes, outer ones of fused silica or plumbago, sufficient insulation for quick reading may be secured.

Again, by means of graduated screens so that the point at which a mark ceases to be visible is read, a field for development of a rapid reading pyrometer is indicated, and for final record a photograph through a chessboard type graded negative at constant distance and pin-hole with constant spring shutter is again a promising line to follow up.

I would emphasize that the work will be better done by an eye trained at reading in a closed ended tube as indicated, than by any pyrometer which takes above 15 seconds to give a reading of the work treated.

A misused or inapplicable highly scientific instrument is a most dangerous tool to introduce into the actual factory.

Mr. W. Bowen (Leeds) (*communicated*): Referring to the paper by Mr. Cosmo Johns, I take it that his object as a metallurgist is to control the temperature of the steel before pouring; in which case, I would suggest that the proper place to measure his temperature is when the steel is inside the furnace, and that temperatures taken subsequent to tapping the furnace serve to control the final pouring temperatures only.

Mr. Cosmo Johns appeared to place too great confidence in the accuracy of his readings within ± 5° C. at the pouring temperatures of steel. In the light of the paper by Dr. Griffiths, his appeal to the pyrometer makers to construct an instrument accurate to within ± 2° C. at these high ranges would seem to be unnecessary at the present stage. Dr. Griffiths states (p. 21): "The practical difficulties of gas thermometer work at high temperatures are very considerable. . . . Consequently the results obtained by different investigators often show divergencies of serious magnitude." Also, an experiment described by Dr. Griffiths shows that taking the melting-point his results compared within 3° C. under very favourable conditions. These remarks clearly indicate that as yet the scale of temperatures in the region of 1,600° C. is an almost unexplored field even under laboratory conditions, and that readings comparable within 3° C. are considered remarkably good. Hence I suggest that the demand made by Mr. Cosmo

Johns for a pyrometer accurate within $\pm 2^{\circ}$ C. under works conditions of a very unfavourable nature is an ideal one impossible in the present stage of development to fulfil. Any readings obtained for molten steel under works conditions such as Mr. Cosmo Johns describes should be considered very good if they can be relied upon to within 10 or even 20 degrees.

Mr. Cosmo Johns described the careful precautions taken by him in reading the temperatures of molten steel by means of an optical pyrometer. May I suggest that now that he has realized the necessity for such precautions, he would probably secure equally comparable readings by the use of the simpler radiation pyrometer by adopting the same precautions.

Mr. Cosmo Johns uses an emissivity factor of 0·50 in correcting the temperatures of Table I of his paper, and a factor of 0·40 in Table II. I fail to see how he arrives at these emissivity factors in the two cases. It appears to me a very difficult matter to ascertain an emissivity factor to correctly fit the case, seeing that he acknowledges a difference between the apparent temperatures at the top, middle, and bottom of the same stream ; also that he probably experiences occasional flashes of light at times, and possible haze at other times, momentary though they may be.

Mr. Carter in the discussion has apparently no recent experience of at least one firm manufacturing pyrometers, when he states that the manufacturers neglect to advise and visit their customers when trouble arises. This is not the case in general.

Professor J. O. Arnold, in responding to the Chairman's invitation to reply, said : I have only one remark to make in reply, and that is this. Dr. Hatfield said he would present to us the facts with regard to pyrometry of the Siemens furnace. These facts he could have obtained from the University records from 1910 onwards. The practical point about the Siemens furnace that we have arrived at to-night is this, and with it I quite agree: that the flame temperature inside the Siemens furnace is from 1,700° to 1,750° C., and that of the molten metal varies from perhaps 1,575° to 1,525°. These figures, which Dr. Hatfield has confirmed with a thermocouple, are extremely interesting, and I think we may take it that we have by this discussion arrived at these two solid facts.

Mr. Cosmo Johns, in reply to the discussion on his paper and the communications received after the meeting, writes that he is pleased that so much interest has been aroused in the subject. Unfortunately, many of those who discussed the paper failed to notice that all the observations on liquid steel recorded were made to determine its "apparent" temperature, and that the accuracy claimed only referred to comparative readings obtained with the particular type of instrument employed by trained observers with long experience under the conditions described in the paper. No suggestion was made that the readings employed could be corrected to give real temperatures on any of the accepted scales to the degree of accuracy mentioned. What was claimed, and the claim is now repeated, is that under the most favourable conditions the "apparent" temperature of "clean" surfaces of liquid steel can be read to $3^{\circ} \pm$ on the scale of the instrument employed, and under ordinary works conditions to something less than $5^{\circ} \pm$.

The degree of accuracy obtained depends on several factors, and it might serve some useful purpose if these are briefly referred to. If the instrument employed uses monochromatic light, readings can be reproduced with greater accuracy than when rays of more than one wave-length are transmitted. In the best type of instrument, the line dividing the two

halves of the field entirely disappears when correct adjustment has been made by the observer. Accuracy in this case depends on the skill of the observer and the quality of his eyesight. As a rule, not less than three months' training is required for an observer to acquire sufficient skill in the use of an optical pyrometer for the work described in the paper. The records given were made by an observer who has been engaged for three years in regular practice. Three observers have been tried with the same instrument on the same clean surface of liquid steel, and the readings they obtained always varied less than 10° from each other, and on several occasions the total variation was only 5°. As a rigorous test of the degree of accuracy with which readings might be reproduced, a trial was arranged with three observers, using the same instrument. The object selected was the interior face of a furnace wall kept as nearly constant in temperature as possible. The scale of the instrument was covered with a paper shield, and after the observation had been made the screen was removed and the reading noted by the present writer and one other observer, who was waiting his turn to use the instrument. When the reading had been noted the pointer was displaced and the paper shield placed over the scale before the instrument was handed back to the original observer to reproduce the reading. The scale was read by estimating fractions of the divisions to the nearest quarter with a pocket lens. The results were as follows :—

Observer.	Readings.	Observer.	Readings.
Y	1,360	W	1,357·5
W	1,360	X	13,62·5
W	1,360	Y	1,360
Y	1,360	Y	1,362·5

The apparent temperatures given in Table III of the paper were made under similar rigorous conditions. The conditions were favourable in that the steel was at a lower temperature than when it issued from the tap-hole. The lower the temperature of the liquid steel, the greater is the accuracy with which observations can be made and repeated. As the effect of distance, angle of view, and curvature of surface of the liquid steel has not been completely investigated, it was decided to adopt a standard position for recording purposes. In deciding on the particular position to be adopted and the surface to be observed, the theoretical considerations came under review and many experiments made before a decision was arrived at. The suggestion made by both Mr. Bowen and Mr. Greenwood, that the temperature should be determined within the furnace and not when the steel has been tapped, amounts to a counsel of perfection. There does not appear to be any method available by which the temperature of the steel in the furnace can be determined with the rapidity and accuracy required. Control can, however, be effected by determining the "apparent" temperature of the surface of the slag in the furnace. This is being done daily in more than one works. The remarks of Mr. Greenwood, that he found that light emitted from liquid steel was polarized, and that the variations with different angles of view were of the order found with platinum, are of great interest. Dr. Burgess* found that polarization effects with liquid steel were nearly negligible, and such is the experience of the present writer. It is to be hoped that Mr. Greenwood will be able to find an opportunity of repeating and extending his investigations on this point.

* Technologic Paper 91, Bureau of Standards.

It might interest Mr. Greenwood, and possibly other workers in the same field, to know that the present writer discarded the tripod for use with optical pyrometers. The instrument is held in the hands of the observer. For routine works readings a single observer can use the instrument and also keep the rheostat adjusted to give a constant current, but for the apparent temperatures given in the paper one observer used the instrument while the other looked after the accumulator box and adjusted the rheostat when necessary. With skilled observers it is possible to take a reading of the surface of the bath in the interval when gas is off the furnace during the periodical reversal. Inexperienced observers would naturally take more time to adjust the instrument for a correct reading, and in their case it might be necessary to put the furnace "on centre" for half a minute or even more.

Enough has been written to make it clear that optical pyrometers of the correct type can be employed to give readings of the "apparent" temperature of liquid steel of a high order of accuracy. These readings are comparable among themselves. The real temperature of the steel observed cannot be determined with anything approaching the same degree of accuracy.

More observations of the highest possible degree of accuracy are required on the effect of variations in the method of observing plane and curved clean surfaces of steel under various conditions. Instruments capable of being read with the accuracy suggested in the paper are required for such work. It is very desirable that the emissivity of a "clean" surface of liquid steel should be determined again. The value quoted by Mr. Greenwood is certainly too high. That found by Dr. Burgess, viz. 40, is probably a little high for an optically clean surface, though probably correct under most conditions in works practice. The remarks of M. le Chatelier are of special interest. The writer agrees that the corrections applied for the brickwork in Table I are probably too high and possibly nearer that suggested by M. le Chatelier than those given in the paper. The problem bristles with difficulties and much more research is required. The corrected temperatures given for the surface of the bath are, however, in the opinion of the writer very nearly correct. Any criticism must not overlook the fact quoted in the paper, that it has been found possible to fuse into liquid state the purest quartz sand when floated on the surface of the bath. This could hardly be achieved if the real temperature did not exceed 1,750° C.

The Chairman: I have listened with very great interest to what has been said, and I feel I have learned a great deal. We have done a great deal of standardization of pyrometers at the National Physical Laboratory with what I thought was high accuracy, but I confess I never realized that in these instruments the demand of industry was anything approaching two degrees; and it is quite clear that there is ample scope for careful collaboration between the makers, ourselves at the Laboratory, and those who are using these instruments. I will now ask Mr. Watkin to give a brief account of his paper, dealing with quite another branch of our subject.

THE MEASUREMENT OF HIGH TEMPERATURES BY MEANS OF POTTERY MATERIALS.

Mr. Henry Watkin (Stoke-on-Trent) then presented his paper on "The Measurement of High Temperatures by Means of Pottery Materials," and described the exhibits he showed to illustrate the paper.

Among the natural phenomena which even the earliest races of mankind could scarcely fail to observe may be mentioned the following: (1) that clay becomes soft and plastic under the influence of water; (2) that form can readily be given to it when in the plastic state; (3) that whatever form is given is retained when subjected to a suitable degree of heat. This knowledge was evidently early acquired, for we read in the Book of the Chronicles the names of a family of potters who dwelt with the king for his work, with the following significant sentence: "And these are the ancient things" (B.C. 1400).

The materials used, the formative properties, and the effect of heat upon the same, are the essential requisites for the pottery manufacture. The distinguishing feature of all the materials used in the product lies in the fact that they must be capable of resisting the action of intense heat without distortion or destruction. These materials include the silicates of alumina or clays, the oxides of silicon, in the form of quartz, sand, or flints, the felspars in great variety, baryta, lime, magnesia, phosphate of lime, and metallic oxides of almost limitless extent, etc., while the fuels needed for the firing, including wood, coal, gaseous and liquid fuels, are found in some form or other in all countries.

The clays vary very much as to their principal property, that of plasticity, and hence *the more plastic clays* would be those likely to be used by the most primitive races, because easily prepared and readily formed, and further, because they would harden at the lowest temperatures. An excess of heat would, however, cause them to go out of shape during the firing; hence the need for the addition of some more refractory material to overcome this disadvantage.

The less plastic clays would require to be made plastic by the ageing process and the addition of organic agencies, etc., and the purest, the least plastic clays, would require not only to have plasticity imparted to them artificially, but would need to have some fluxing matter added to give strength.

A notable exception to this occurs in a kaolin, which is so plastic that the vase shown was made without any admixture whatever by the process of throwing and turning, which will be well understood by any potter.

These three considerations have during the ages led up to the present innumerable compositions for the pottery and porcelain manufacture,

commonly called bodies or pastes, which depend largely for their value upon the correct amount of heat given to each particular composition, and explain why so many other than plastic materials are required in their various compositions.

The effect of heat upon the various materials may be summarized as follows: (1) it diminishes the size of the clay product while hardening and retaining permanently the form of same; (2) it renders the articles made therefrom partially or completely impervious to moisture, according to the purposes for which they are required; (3) it fuses the glaze and provides a perfectly smooth glass on the surface of the otherwise rough body; (4) it fuses either upon or under the glazed surface any decoration that may be given, and renders the same permanent.

The intensity or degree of the fire required to bring about these results varies according to the materials used and the ends obtained. The varieties of pottery made throughout the world must always have been a source of interesting inquiry as to how they had been produced, at what period, from what materials, and at what temperatures, etc.

Every class of pottery and porcelain has its own particular minimum and maximum degree of firing, whether it be ancient or modern. In fact, this is true also of all the materials used in the manufacture. All the clays, bodies or pastes, glazes, colours, golds, silver, lustres, etc., have a definite firing-point, and therefore a knowledge of these is of the utmost importance to the manufacturer.

The following tables will show the wide differences which occur between plastic clays and felspars, as examples.

Table I shows how different are the contractions between five clays under fire, taken out of twelve such clays out of the same mine, and tested at the same time under like conditions.

TABLE I.

Contraction per cent.

	No 20.	No. 6.	No. 18.	No. 4.	No. 15.
960° C. ..	8·0	7·7	6·2	5·3	8·9
1,180° C. ..	14·3	9·8	9·8	8·5	14·3

The variations in colour will be seen on inspecting the trials shown, while the variations in the felspars will be seen by inspecting the samples shown and by use of Table II. The natural felspar and the

TABLE II.

Sample No.	Colour before Firing.	Order of Fusibility.	Firing Temperature.
9	Very dark salmon	1	Cone 10
7	Dark salmon	2	Ditto
4	Salmon	3	Ditto
10	Pale salmon	4	Ditto
11	Paler salmon	5	Ditto
8	Grey	6	Ditto
5	Light grey	7	Ditto

fired piece in each case were originally broken in two, one part kept and the other fired. By putting the two pieces together it will be seen at once the great change the firing has effected.

It is not enough to know that felspar fuses, but the temperature at which it fuses. The means by which many of these firing-points were known to the potters of a century or more ago leaves no doubt that they must have possessed some system of pyrometry worthy of the name, or they could not have produced the wonderful works of art found in almost endless variety. What system was this ?

In my opinion the principle upon which these were founded was the fact that the materials used in the manufacture afforded to the potter a fairly accurate means of knowing when the required degree of heat was attained. The only thing needful was that he should be able to withdraw sample pieces of the ware from the oven at intervals during the firing, from which, without any other instrument whatever than those of the senses, he could judge fairly well, for all practical purposes, when he had obtained the desired result. Taking those of sight, feeling, and hearing, we can see what information was gleaned therefrom.

Sight.—(1) The different colour of the flames would not long escape his attention, and he would soon learn the progressive changes from

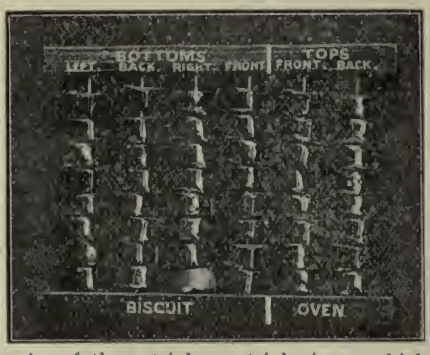


FIG. 1.—Shows a series of these trials, or trial pieces, which have been placed in six different parts of the same oven, viz. the left, back, right, and front quarters, and taken out at eight different stages of the firing.

incipient red through dull red, dark cherry red, light cherry red, deep orange, yellow, light yellow, white, to incandescence.

(2) The changes in colour which red clays undergo when fired, first to light red, then progressively and perceptibly darker with increasing heat, are shown in samples submitted (Fig. 1). The effect is more distinct and measurable if the samples are covered with a soft glaze before firing, which develops the colour.

(3) Translucency of the trial-pieces in such productions as parian bone china, felspathic porcelain.

(4) The development of the rose tint in enamelling colour.

(5) The diminution of bulk, or contraction.

Feeling or Touch.—The roughness of the material, the hardness, the weight, the density, would be appreciable, and, in the hands of an experienced fireman, well able to confirm the indications given to his sight. This would be still further assisted by touching the trial-pieces with the tongue: when only feebly fired the piece adheres to the tongue and decreases as the firing is increased.

Hearing.—The goods when fired, if struck by a piece of metal, wood, or by another piece of the same pottery, give out sounds which vary according to the degree of heat at which they were fired, etc., and, suitably selected, may give the whole musical scale. I remember, when a youth, a fellow-worker at a Burslem pottery of a musical turn of mind amusing a number of workmen by placing a nest of ordinary jelly cans in a row, the largest at one end and the smallest at the other, in such a manner as to form the scale, and playing popular airs upon the same very creditably. While this was proceeding the principal, unobserved, was listening, and when he was sufficiently entertained, made his appearance and simply remarked, "When you have done with those, Harry, will you be good enough to put them in their proper place?"

All the foregoing methods are still used, and for very many branches

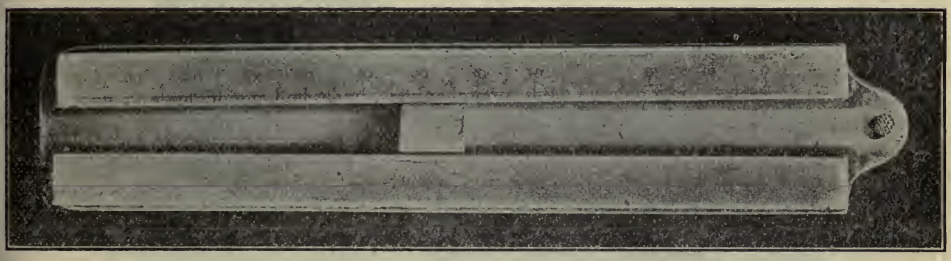


FIG. 2.

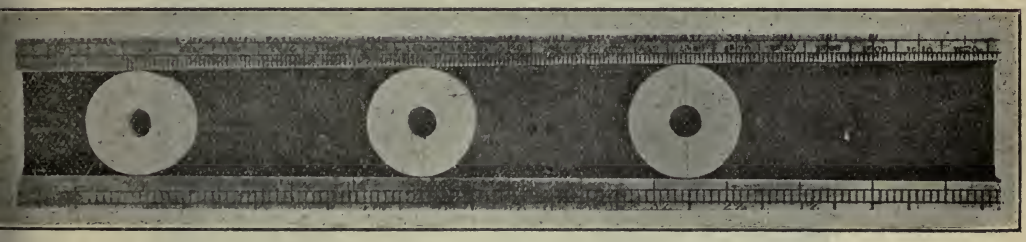


FIG. 3.

of the pottery manufacture they are for all practical purposes sufficiently reliable. Consequently, they are not likely to be dispensed with very suddenly, based as they are on something more than mere rule of thumb, viz. human intelligence and experience.

It will readily be appreciated that while some of these tests could be standardized so as to be compared from time to time by the same person, they could not be easily conveyed from one person to another, and, further, that obviously the most measurable of these various changes was and is the contraction which takes place in the pottery or porcelain itself. That this *contraction* or diminution of bulk which takes place during the firing could be conveniently measured was the discovery of the great Josiah Wedgwood. After years of patient experimenting he accomplished his object in 1772, and in 1782 he communicated a paper to the Royal Society, which was published in vol. 72 of the *Philosophical Transactions*,

extracts from which are given in a pamphlet printed by Joseph Cooper, London, 1784, a copy of which is before me.

The WEDGWOOD PYROMETER, based on the principle of the contraction of pottery materials under the influence of heat, was in his day probably the best instrument in existence for the measurement of high tempera-

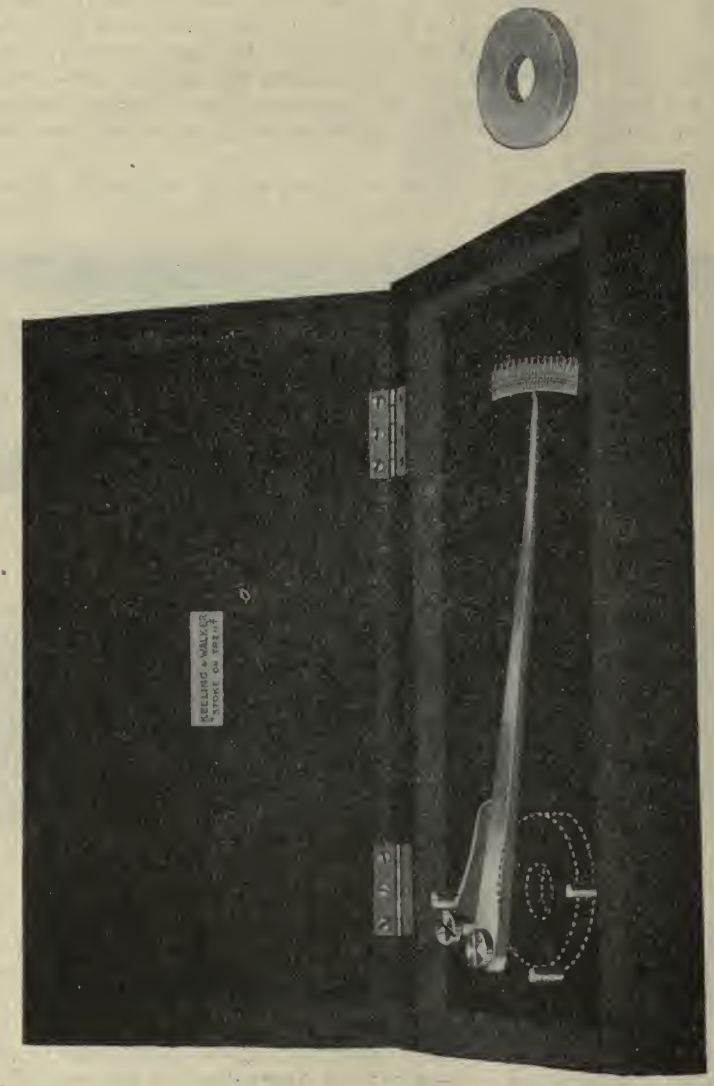


FIG. 4.

tures. Its usefulness, however, was limited to the degree of heat needed to bring about the maximum contraction of the clay or body used for the test-pieces; nevertheless, as this temperature was much higher than the English potters then required, it was negligible from the potter's point of view.

By the courtesy of Messrs. Wedgwood & Sons the original pyroscope

used by Josiah Wedgwood himself is on view, and is shown here in Fig. 2.

In recent years it has been considerably improved, first, in the materials of which the test-pieces are made; second, in the form and method by which they are made; and third, in the instruments by which the test-pieces are measured.

The *first* of these was effected in 1900 by the writer's use of a round disc made under pressure from steel tools, with a hole through the centre for the purpose of being readily withdrawn by an iron rod during intervals of firing, and made of materials which contracted progressively and regularly through a much wider range of temperature. The steel

FIG. 5.—Seger Cones or Pyro Cones.

gauge used for measuring these pieces is made in such a manner as to measure accurately to a thousandth part of an inch, and also shows the percentage contraction of the piece corresponding to same. The disc is placed in the groove at the widest end and the distance to which it will pass registers the degree of contraction. (See Fig. 3.)

Buller's trial-rings followed, based on the same principle, and are shown in Fig. 4. This system, which has been adopted by many of the leading potters throughout Great Britain, consists of a specially made clay ring, measuring 2½ in. in diameter and registering o on the gauge plate. As the ring contracts during the different stages of firing, the changes as shown on the gauge are noted on special charts provided for the purpose, and a practical guide and check upon the firing is thereby obtained. The system is especially useful, as a record is gained of the work done by each man in charge of an oven, and continued use shows that the contraction recorded, together with the time taken to obtain the said contraction, is a most useful and reliable guide.

About fifty-four years after Wedgwood had discovered the most obvious measurable change in pottery materials under the influence of fire, viz. the contraction of clay, Messrs. Vogt and Light, of Paris, perceived the advantage of the less obvious change, viz. the fusibility of the materials.

Taking of these china clay, felspar, and lime, etc., they made a series of mixtures with different degrees of softening-points made up into cones, which distorted in such a manner as to be easily observed when they reached certain degrees of heat. Improvements, as usual, followed, and in 1886 Seger made up a series of cones having melting-points from 1,150° to 1,390°, which he numbered 1 to 35, which were subsequently increased by Cramer, who produced a series with lower melting-points from 590° to 1,130°, and which were numbered 022 to 01.

By using three or four of these cones in the observation-points of the

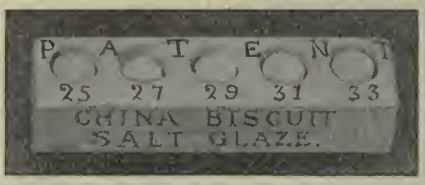


Fig. 6.

1 3 5 7 9

Fig. 7.—Section before Firing.

1 3 5 7 9

Fig. 8.—Section after Firing.

oven the fireman can see by the collapsing of the cones how the changes necessary are progressing (Fig. 5). These cones were introduced to the English potters about 1892, when the author first adopted them.

It is very gratifying to say that these cones are now being made in England, at the Central School of Pottery, Stoke-on-Trent.

A still further use was made of this principle by the production of the heat recorders and discoverers by the writer in 1899, as shown below.

The recorder (Fig. 5) is simply a block of very refractory ware, with five circular recesses sunk into its top face. In these recesses are placed little pellets of fusible materials of definite composition and melting-point. The fusion-point of each mixture has been carefully and accurately determined by comparison with a standard electrical pyrometer. The recorders are sent out with a special wrapper, which serves to retain the loose pellets in their place. This wrapper should not be removed, as it will readily

burn away. After the firing it is a matter of indifference whether the pieces that are loose drop out, as those pieces that fuse will always remain attached to the recorder.

Figs. 6 and 7 show the change produced in the pellets by firing, and at the same time show the progressive nature of the record.

How to read.—The number which has become slightly rounded on the edge, as shown in No. 7 (Fig. 8) below, should be regarded as the number obtained. Should one, however, be rounded like No. 5, while the next one remains unaltered as No. 9, then the number between should be taken as the reading.

While specially designed for simply recording temperatures attained in parts of ovens, etc., inaccessible to observation, the recorders may also be used with advantage as pyrometers. They have proved very useful as such to many industries, including the following: pottery and porcelain manufacturers, brick-tile makers, gasworks, glassworks, engineers for annealing furnaces, smelting furnaces, rolling mills, enamellers, etc. By the use of these the firing-points of the pottery and porcelain manufacture, both at home and abroad, were obtained, as given below, and which were published as far back as 1902.

The cheapness of the recorder and the small space it requires will enable manufacturers to ascertain the heat of the oven or kiln at many more points than is at present customary, and will thus lead to the great desideratum of more even and regular firing.

By the use of these recorders the writer was able to determine the following data:

TABLE III.

Series of Recorders most suitable for Different Classes of Ovens and Kilns.

							° C.
A	1	3	5	7	9	Enamel kiln	600 to 815
	3	5	7	9	11	,, ,, ...	670 to 855
	5	7	9	11	13	Hard kiln for marones, etc. ..	710 to 900
	7	9	11	13	15	,, ,, ,, ...	750 to 940
	9	11	13	15	17	(Soft) Glaze kiln for tiles, etc...	815 to 980
B	11	13	15	17	19	(Hard) Glaze kiln ,, ,, ..	855 to 1,020
	13	15	17	19	21	(Easy) Glost oven and Rockingham	900 to 1,060
	15	17	19	21	23	(Hard) ditto	940 to 1,100
	17	19	21	23	25	Earthenware biscuit oven ..	980 to 1,140
	19	21	23	25	27	Hard ,, ,, ,, ..	1,020 to 1,180
C	21	23	25	27	29	Tile biscuit and granite biscuit	1,060 to 1,230
	23	25	27	29	31	Parian biscuit and glazed bricks	1,100 to 1,280
	25	27	29	31	33	China biscuit and salt glaze ..	1,140 to 1,320
	27	29	31	33	35	,, ,, ...	1,180 to 1,380
	29	31	33	35	37	Hard paste porcelain	1,230 to 1,455
D	31	33	35	37	39	Hard paste porcelain	1,280 to 1,480
	33	35	37	39	41	Refractory products	1,320 to 1,520
	35	37	39	41	43		1,380 to 1,580
	37	39	41	43	45		1,435 to 1,630
	39	41	43	45	47		1,480 to 1,670

TABLE III—*continued.*

							° C.
E	41	43	45	47	49	Research work	1,520 to 1,710
	43	45	47	49	51		1,580 to 1,750
	45	47	49	51	53		1,630 to 1,790
	47	49	51	53	55		1,670 to 1,850
	49	51	53	55	57		1,710 to 1,920
F	51	53	55	57	59	Research work	1,750 to 2,000

It will be seen from the previous table (Table III) that all the varied colours, golds, lustres, etc., usually fired in enamel kilns, are fired at temperatures below 940°. Many of these are fired up at 690° to 730°, and if taken to about 800° are faulty or completely spoiled.

From Table IV it will be seen that a coral red colour which was good at No. 3 to 4 recorder=670° to 690°, was faulty at No. 5=710° C., and completely spoiled at No. 6=730° C.; that the bright gold usually called liquid gold was not fastened on the glaze by the fire at No. 2=650°, was good at No. 3=670°, hard at No. 4=690°, and spoiled at No. 5=710°, etc.

TABLE IV.

Firing-points most suitable for Certain Golds, etc., as determined by the Recorders.

	Easy.	Good.	Hard.	Bad.
Best Burnished Gold.				
On white body	3	4—6	7—8	9
On jet body	3	4—6	6½	7
On blue glaze	3	4	5	6
Liquid Gold.				
On white body	4	4—6	7	8
On jet body	2	3	4	5
Coral Red.				
On white body	2	3—4	5	6

Easy means gold was not fastened, and wiped off under rag; *good* means properly fired, satisfactory gilding; *hard* means gold difficult to burnish well, and does not take a high polish; *bad* means cracked, flecked, or impossible to burnish.

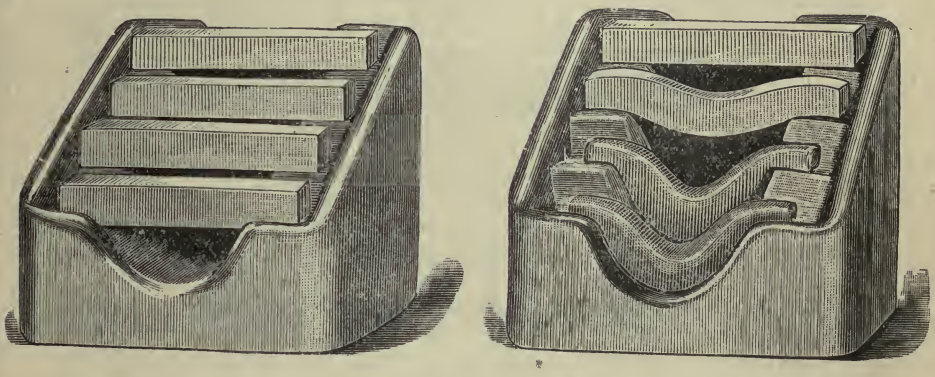
These figures would not necessarily be applicable to other bodies and glazes than those from which the above data were taken.

Also, it will be seen from Table III that hard glaze kilns for tiles are usually fired up at something below No. 19=1,020° C., and glost ovens something below No. 23=1,100° C. The maximum difference then is about 80° C. The differences in the colour given to a glaze by certain metallic oxides may be described, showing how important it is that these points should be known definitely.

The specimen samples before us show that an orange-red glaze produced by uranium oxide at a temperature of 950° C. is turned to a brown at 1,050° C.; a purple glaze produced by manganese at 950° C. is turned to a brown at 1,050° C.; a red-brown glaze produced from chromium at 950° C. is turned into a green at 1,050° C.; a turquoise glaze produced from copper at 950° C. is turned into a green at 1,050° C.; a yellow glaze from chromium at 950° C. is turned into a green at 1,050° C.; a black glaze produced from iridium at 950° C. is turned into a grey at 1,050° C.

Table V will show how important it is that this information should be available for a more satisfactory conduct of the firing operations.

It will be noticed that in each case the contraction is greater in the case of the smaller article, although fired in the same spot at whatever temperature and for the same length of time. It would appear that



Before using. After using.

FIG. 9.—Holdcroft & Co.'s Thermoscope.

the larger bulk required either a longer time at a given heat or a higher temperature to effect equal contraction to the smaller bulk.

TABLE V.

	Body No. 1.		Body No. 2.		Body No. 3.	
Size of test-piece ..	100 × 100	41 × 20	100 × 100	40 × 20	100 × 100	40 × 20
Contraction %—						
Fired to 1,140° C.	6·01	6·81	6·75	8·53	6·40	7·87
,, 1,230° C.	8·00	9·15	7·77	9·20	8·00	9·43
,, 1,280° C.	8·00	9·18	7·67	9·62	8·50	9·43

These fusible mixtures were still further modified in or about 1898, when they were made in England for the first time by Messrs. Holdcroft & Co., who made the mixtures up into bars instead of cones, which, suitably suspended in a refractory case, are more easily read or observed by the sagging which takes place during firing when the temperature is reached which produces the same, unlike the Seger cones, which sometimes lean in the direction of vision, and consequently the distortion is not so easily observed.

The bars represented are of varying composition and are most carefully compounded and tested before being allowed to leave the works. They are numbered from 1 upwards; the higher the number the higher the temperature required to cause them to sag in the middle, as shown in the illustration, Fig. 9.

A further form of fusible cone, designed by Professor Cobb, is now being made at the Central School of Science and Technology, Stoke-on-Trent, having the following characteristics:

1. They are made wedge-shape with one side flat, towards which they always fall.

2. They are larger than the German cones, consequently not so easily affected by stray flames.

3. They are more easily seen at the high temperatures than the old cones.

Coloured end. Exact size.

FIG. 10.—Wenger's Calorites.

These articles, called "calorites," are used for indicating the heat of kilns or ovens; they are cylindrical in shape, and are 2½ in. (65 mm.) long × ¼-in. (7 mm.) diameter.

The calorites are placed in the kilns or ovens vertically on calorite sockets, and on firing they bend and then melt down (in proportion as the heat rises), and may be watched from the trial holes.

The cylinders are of different composition, and are coloured at one end. The colours correspond with a list given with same, indicating their point of fusion. The end remains coloured after fusion, allowing of their being recognized, which is not the case with other kinds of temperature indicators, the marks of which are obliterated after fusing.

The extremely low cost of the calorites allows of their being more extensively used, and they may be placed in all parts of the kilns or ovens, giving a record of the different degrees of heat to which they have been subjected.

All these various forms of pyrometers based on the principle of the softening-points of ceramic mixtures are very extensively used for industrial operations where high temperatures are necessary. They have, however, we must confess, a serious limitation, since they do not register the length of time at which the heat remains at any particular temperature during the firing.

In conclusion, while admitting these pyrometers are not perfect, there need be no hesitation in claiming that they have been, and now are, of enormous advantage to every form of high temperature industrial process, and until something far superior from every point of view is forthcoming, or rather is at hand, it will be a wise policy to "Prove all things; hold fast that which is good."

DISCUSSION.

The Chairman: I do not know whether members have had an opportunity of carefully studying this paper, but you will find therein some extremely interesting practical methods of temperature-measurement that must be of great value in the industry in which Mr. Watkin is engaged.

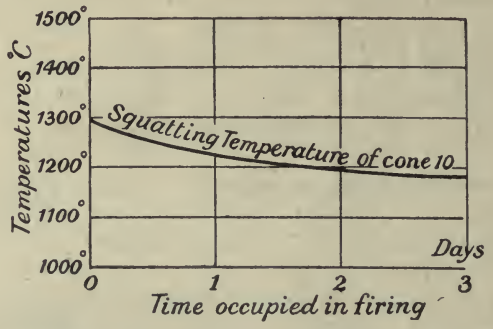
Major C. W. Thomas (*communicated*) : I much regret I shall be unable to attend the discussion, which I should have been interested to hear, more especially from the point of view of high temperatures in the burning of refractories. In my opinion the measurement of the actual temperature attained in the burning of refractory materials is of secondary importance. What is important is to ascertain whether the shrinkage of the material has taken place to a sufficient extent. Various methods of temperature measurement based on this principle have been used in the pottery industry, most of which are rather too delicate for ordinary refractory work. It seems to me, however, that any form of instrument, by which the progress of the shrinkage of a standard-sized block (made from the same refractory material as the kiln charge) can be measured, should give a burner complete control of the finishing temperature.

Further, inasmuch as the shrinkage of a clay body is within limits regularly progressive, the extent to which it has been carried at any given point of time should be an adequate guide to the amount of heat-work done.

Mr. W. J. Rees (*communicated*): Mr. Watkin's paper usefully directs attention to the various methods of utilizing the contraction and softening of varying mixtures of kaolin, felspar, quartz, lime, etc., as indicators of heat-effect. Seger cones and other similar devices such as the Watkin heat recorders and the Holdcroft thermoscopes, based on the softening of ceramic mixtures, are undoubtedly of considerable value in controlling many firing operations, particularly those conducted in kilns. They do not, however, measure temperature, but rather heat-effect, and the very common practice of using cone numbers with temperatures in parentheses should certainly be discouraged. The falling over or bending of these cones or bars depends to a great extent on the rate of heating, as well as on the temperature reached. The reduction in viscosity is gradual, and a degree of viscosity sufficient to cause collapse of the cone can be reached in a short time at a higher and in a longer time at a lower temperature. In the lower numbers of cones containing oxide of iron, the atmosphere of the furnace or kiln may be an important factor in determining the time taken to cause bending, as the formation of ferrous silicate will reduce viscosity, whilst ferric oxide would act in the opposite direction. The divergence between the bending temperatures of cones with rapid and slow heating (the temperature being determined by thermocouples) has been repeatedly demonstrated experimentally.

Dr. J. W. Mellor (*communicated*): There are several interesting points about the contraction and fusion types of pyroscope which Mr. H. Watkin has reviewed. Perhaps the most important of these is the erroneous impression that the cones, bars, calorites, or recorders, *per se* indicate exact temperatures. This impression has arisen because an approximate squatting temperature is assigned to each cone. The drop in the curve

on the diagram, passing from left to right, illustrates how an extension of the time of firing lowers the squatting temperature of the cones. An ordinary china biscuit oven, for instance, maturing at cone 10 in



three days, would have been fired to 1,300° according to the schedule of temperatures; as a matter of fact the actual temperature read by the pyrometer does not reach 1,200°. The specified squatting temperatures of the cones have been determined by heating the cones for from two to four hours up to the specified temperatures; if the cones be "soaked" for a long time at a lower temperature they will squat at a lower temperature than the specification. In actual firing both time and temperature are of prime importance. A prolonged soaking at a relatively low temperature may do the same work in maturing a body or glaze as a quicker fire at a higher temperature. The fireman wants to know what work the heat has accomplished on the goods being fired, and this is indicated by the squatting of the cone; the actual temperature attained is of little importance industrially, provided the purpose of the firing has been accomplished.

Whatever be the nature of the reaction which takes place when the goods are fired, it is tacitly assumed that the characters of the cone and clay are so much alike that the squatting temperatures of the cones and the maturing of the goods in kiln or oven are effected by a similar reaction, and that the temperature coefficients of the two reactions are the same. This is quite an assumption, and examples are known where the speeds of the two reactions (cone and clay) are similar under one set of conditions but different under another set of conditions. The idea may perhaps be more clearly expressed in symbols. If U_1, V_1 respectively denote the speeds of the reaction between cone and a clay at a temperature t_1, and U_2, V_2 the corresponding speeds at a temperature t_2, if the two reactions have the same temperature coefficients

$$\frac{U_1}{U_2} = \frac{V_1}{V_2}$$

and consequently the magnitude of $U_1V_2 - V_1U_2$ represents the error involved in assuming that the two reactions have the same speed; and the greater this difference, the greater the slope of the curve in the diagram.

Another point. If the pyroscopes are made without a reducible metal oxide, it makes no difference to the indications whether they are fired in oxidizing or in reducing atmospheres; but this by no means applies if the atmosphere be contaminated with certain forms of dust which flux readily with the materials of which the pyroscope is made. Some forms of dust "harden" the surface of the pyroscope so as to form a more refractory shell. In a bad case, the interior may then burst through

and flow away, leaving the refractory shell standing. Again, the dust may form a more fusible mixture with the materials of which the pyroscope is made, and in that case the indications of the pyroscope may be all wrong because the pyroscope fuses too quickly. Furthermore, the pyroscopes may be placed in the track of the flames at one time, and not at another; this, again, will make the readings all wrong. It is therefore necessary whenever there are risks of this kind to protect the pyroscope as much as possible from the disturbing conditions.

The point raised by Mr. Watkin on p. 136 is interesting. It seems to be a special case of a phenomenon I discussed in the *Transactions of the Ceramic Society* (9, 126, 1909). Vitrification or fusion proceeds from the surface inwards, and when the reaction is arrested while in progress, the percentage contraction will be larger with small pieces because of their larger surface per unit mass.

Mr. Henry Watkin: (*communicated reply*): In reply to the helpful contributions to this discussion, I wish to say in the first place how much I appreciate the remarks of Mr. Thomas, with whom I am in perfect agreement as to the value of the contraction of clay within certain limits as a measurement of high temperatures. I have used these successfully for very many years, but since the introduction of the fusible cones I have invariably used both at the same time, placing some of each in the trial saggars with very great advantage, one acting as a check upon the other.

In regard to the remarks of Mr. Rees, it has already been admitted that it is not claimed that any other pyrometers under discussion are perfect, but it may be said, first, that in many forms of ceramic work the pyroscopes in some form or other are more useful than any other known substitute: (1) the temperatures are approximately correct, and that on two to four hours' heating; (2) that instead of having an arbitrary scale of numbers, it is much more satisfactory to link them up with a recognized thermometric scale; (3) as there is no compound of iron used now in the lower series of cones, the objection is invalid.

Dr. Mellor's remarks deal with the importance of clay and slow firing, which to my mind is worthy of very careful investigation. It will not only be interesting but valuable knowledge to find that we can acquire the same effect, at a temperature of, say, 1,450° or 1,500°, by firing a longer time at 1,200° to 1,300°.

BASE-METAL THERMOELECTRIC PYROMETERS.

Mr. Chas. R. Darling, A.R.C.S., F.I.C., contributed the first of two papers on "Base-metal Thermoelectric Pyrometers."

One of the most notable features in the progress of industrial pyrometry during the last decade has been the widespread introduction of base-metal thermoelectric pyrometers. This has been due in part to the steadily increasing cost of platinum and kindred metals; but apart from this consideration base-metal couples possess distinct advantages. One of these is the development of an e.m.f. several times as great as that given by a Le Chatelier couple of platinum and platinum-rhodium alloy, which enables more robust indicators and recorders to be used, or a more exact reading to be taken over a given range. Another is that the pyrometer itself may be strongly constructed, and thus made less liable to injury in workshop use. Although inferior to the Le Chatelier couple with respect to the temperature range over which they may be used—the upper limit being 1,000° C. for continuous use—base-metal couples still enable temperatures to be measured which comprise many industrial processes, such as hardening, tempering, and annealing, and have proved satisfactory in practice for such purposes.

The couples commonly employed are iron-constantan; two iron-nickel alloys of different composition; and two different nickel-chrome alloys, known as Hoskins' alloys. In some cases iron alloys containing aluminium are also used, the couples chosen being such as to yield a relatively high e.m.f., increasing uniformly with temperature. Some of these alloys, as Kowalke * has shown, tend to change on heating continuously, in such a manner as to alter the e.m.f. of the couple, and so seriously to affect the calibration of the scale. This danger may be reduced to a minimum by the careful selection of the alloys used, and due care in their manufacture; and my own experience of British base-metal pyrometers is that they are quite reliable if used within the prescribed limits. Prolonged heating near the limiting temperature appears to affect all alloys, even those of platinum and rhodium, and thermoelectric stability can only be ensured when the common working temperature is well below the limit to which the couple may be used for an occasional reading. The safe limits for steady and casual heatings are usually notified by the maker, so that serious errors may be avoided by the user following the instructions given. When iron is used as one of the metals in a couple, it may be prevented from oxidizing

* *Transactions of the American Electrochemical Society*, vols. xxiv. (1913) xxvi. (1914).

by coating with aluminium, as shown by Ruder,* who has devised a process known as " calorizing," which resembles that of " sherardizing " with zinc. Painting with aluminium paint, and heating to a red heat to remove the varnish, although not so durable as calorizing, greatly reduces the rate of oxidation of iron at high temperatures, and thus lengthens the life of a couple containing iron as one of the members. A careful investigation recently made by Kowalke (communicated to the American Electrochemical Society in October, 1917) shows that coating with aluminium does not cause any appreciable change in the e.m.f. of the junction. The application of aluminium is equally useful for protecting iron pyrometer sheaths; and the present writer has used it with success in all work involving the heating of iron since the publication of Ruder's paper.

Up to the present, no base-metal couple has been brought into use capable of being used continuously at temperatures above 1,000° C.; and it has consequently been necessary to use a Le Chatelier couple, or a different type of pyrometer, for higher ranges of temperature. The object of this paper is to suggest a means of extending the range over which base-metal couples may be used, by utilizing the e.m.f. developed by a junction in which one or both of the metals may be in the liquid state. This is rendered possible by the fact that metals such as tin, aluminium, and copper, which could not be used in an ordinary pyrometer in which fusion would destroy the couple, might be used up to temperatures approaching their boiling-points if the junction were maintained. As shown in the following table, the boiling-points of many common metals are sufficiently high to indicate that a temperature of at least 1,500° C. might easily be read by the aid of liquid couples :—

Metal.	Boiling-point, °C.
Aluminium	1,800
Silver	1,955
Tin	2,270
Copper	2,310
Nickel	2,330
Iron	2,450

The question immediately arises whether metals in the molten state develop an e.m.f. suitable for pyrometric work. This matter has formed the subject of an investigation by the author and A. W. Grace,† and the results so far obtained indicate that in general the thermoelectric properties are unaffected by fusion, and that a temperature-e.m.f. curve shows no discontinuity at the fusion-point. Exceptions to this rule are furnished by bismuth and antimony, both of which show an abrupt bend in the curve at the melting-point. In this connection it is interesting to note that bismuth and antimony differ from other metals by expanding on solidification, and, as Northrup has shown, by possessing a lower resistance to electricity in the liquid than in the solid state. Generally speaking, however, change of state from solid to liquid does not affect the thermoelectric properties, and the example shown in Fig. 1, which represents the result obtained with a couple of lead and German silver, may be taken as typical; there being no discontinuity at the melting-point of lead, 327° C. It would therefore appear possible to measure

* *Transactions of the American Electrochemical Society*, xxvii. (1915).

† *Proceedings of the Physical Society*, vol. xxix., part 1, December 1916.

temperatures by the aid of fused couples, and that all that is necessary to apply the method in practice is to produce a working pyrometer on these lines.

Experiments directed to this end have been hindered by many causes, chief amongst which has been the difficulty of obtaining suitable refractories shaped to meet the requirements of the problem. To test the

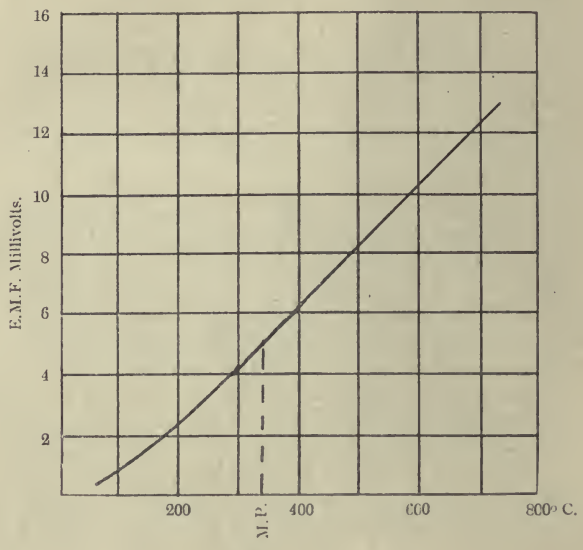


FIG. 1.

feasibility of such a pyrometer, the arrangement shown in Fig. 2 has been used, and has proved satisfactory for experimental work. A graphite block C has two holes drilled into its upper surface so as to contain the ends of two silica tubes, A and B, down which slack-fitting rods of the metals forming the couple were passed so as to make contact with the graphite block. When one of the elements was known not to-fuse at the temperature employed, it was threaded at the end and screwed into the graphite to make a sure contact. The arrangement was inserted in

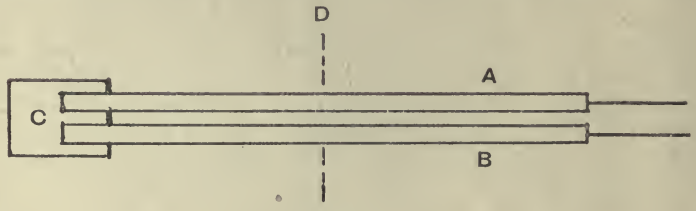


FIG. 2.

the tube of an electric furnace to a depth indicated by the line D ; and on fusion of one or both of the elements the circuit was maintained, the liquid portion in the furnace being continuous with the solid part outside. The ends of the metals at A and B were connected to a milli-voltmeter by wires of the same material, and readings of e.m.f. taken at various temperatures measured either by a calibrated thermal couple or

a radiation pyrometer sighted on the lower end of C. The graphite block serves to prevent the mixing of the fused metals, and the e.m.f. developed is the same as if the metals were actually in contact. At present results up to 1,000° C. only are available, this being the limiting temperature of the furnace used, but the regularity of the increase in e.m.f. with temperature with a number of couples would appear to justify the assumption that the method might be used up to 1,500° C., or even higher. When circumstances permit, the investigation will be carried several hundred degrees higher, a suitable furnace being now available.

In designing a workshop pyrometer on these lines, suitable for use in a vertical position, several obvious difficulties would have to be overcome. It would be necessary, for example, to prevent leakage of the fused metal, and to allow for its expansion on melting and subsequent heating. It would also entail the use of a refractory which is non-porous, and not attacked by the metals at the temperature used. None of these difficulties, however, should prove insuperable ; and if overcome it might be possible to extend the use of thermoelectric methods to measuring temperatures such as that of molten steel. One advantage which a fused-element pyrometer would possess over one made up of wires would be the absence of errors due to lack of homogeneity in the materials ; and given that pure metals were used, the initial calibration would serve indefinitely. Moreover, such a pyrometer would be self-checking ; thus if copper were one of the members of the couple, a short halt would be observed on the indicator on heating or cooling through the fusion-point, when the temperature registered should be 1,083° C. It would be advisable, if possible, to use elementary substances for the couple, avoiding the use of alloys, which might alter in composition on prolonged heating owing to one of the constituents being more volatile, as is observed in the case of platinum-iridium alloys.

The author regrets that under present conditions he is unable to devote sufficient time to the prosecution of this research, but takes this opportunity of indicating a line upon which, using base metals, the range of usefulness of thermoelectric pyrometers may possibly be considerably increased.

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NOTES ON THE REMEDIABLE CAUSES OF UNRELIABILITY ENCOUNTERED IN THERMOELECTRIC PYROMETRY, ESPECIALLY IN SYSTEMS OF THE BASE-METAL TYPE.

Mr. G. E. M. Stone (Newcastle-on-Tyne) contributed the following paper on this branch of the subject entitled "Notes on the Remediable Causes of Unreliability encountered in Thermoelectric Pyrometry, especially in Systems of the Base-metal Type."

There has been a great demand of late, in connection with metallurgical heat-treatment, for a system of temperature measurement conforming to the following requirements:

(1) It must be comparatively inexpensive to instal. (2) It must be of simple and easily understood application to the work in hand by the particular class of workmen employed. (3) The involved apparatus must be of robust nature, not easily broken or put out of order; (4) capable of automatically recording the indicated temperatures, (5) these indications to be within, say, 10° C. on either side of accuracy at working temperatures.

It is proposed to leave on one side discussion of various other methods of pyrometry, together with sundry considerations which we have found in practice seriously to affect their compliance with one or other of the above-named requirements; and in the following notes, to refer particularly to efforts made by various manufacturers to supply these demands, by means of base-metal thermocouples, used in conjunction with pivot milli-voltmeters of robust type.

Systems belonging to this class show great attractiveness in first cost of installation, and in cases where only one or two points in a range of furnaces require pyrometric control, and the fire-rods or "stems" employed are used with a single indicator in connection, and are not required to be interchangeable with other indicators, or with fire-rods of differing lengths, very fair results may sometimes be obtained.

As soon, however, as work in hand increases, and requirements necessitate more than one instrument in use, together with the employment of fire-rods of varying lengths, and recording instruments, in addition to portable indicators, working in conjunction therewith; then it has been our experience to be called upon to investigate numerous instances of peculiar behaviour of the temperature indications, which have caused much trouble and delay in the progress of heat-treatment work.

Briefly, the complaint most frequently made is that readings of temperature are obtained at one time passably correct; then, within perhaps a day's time or the lapse even of a few hours, all other conditions being apparently the same, readings are given which are obviously perhaps 50° C. or more either too high or too low. If now this be rectified by the only method often adopted in these systems, namely by

adjusting a small variable electrical resistance provided somewhere in the conducting wires, it is found that after the lapse of a further few hours or days, as the case may be, the former error has either rectified itself, thus making it appear that interference with the compensating resistance was unnecessary ; or else there exists now an error of entirely different value unaccountably showing itself.

Complaints about the apparatus made to the manufacturers, owing to the user not generally being possessed of either time or suitable instruments to substantiate his complaint by very precise observations and figures, frequently result in dissatisfaction to both parties. Moreover, if the manufacturer's representative attends in order to localize the fault, it very often tantalizingly happens that on that particular occasion fairly good readings are prevalent.

It is with a view to suggesting causes of some of these troubles, which it has been our good fortune with the help of able assistants to remedy, and so to indicate several lines on which, during the manufacture of new apparatus, it would seem possible to prevent their recurrence, that these notes are submitted.

Of course, it is admitted that the non-homogeneity of the materials from which base-metal fire-rods are made has always been, and still is, a serious obstacle to accurate working. Such a state, not necessarily present in new material, and in the cold state, may very soon be set up due to temperature and to heat-treatment whilst in use.

To take as one instance the case of the iron-constantan form of fire-rods, which are much in use with these systems : a thermal curve taken on the material of the iron element shows characteristic change-points, therefore indicating that a molecular change of material takes place in those portions of the stem which attain these temperatures. Then, after heat-treatment for a very short time, a varying crystalline state in different portions of both elements is more or less permanently produced, so that if the furnace into which the stem be inserted is not at a uniform temperature, or the rate of heating or cooling be varied, the electromotive force values given by the couple for the same temperature at its tip will not be equal from time to time for these reasons ; therefore, also, the presence of nickel, or any material possessing periods of molecular transformation, is capable of producing results of similar nature.

An interesting experiment is to take such a stem, which has been in use but a short time, and to cut one of the elements carefully into halves, lengthwise ; attaching the two wires from a millivoltmeter one to each of the resulting strips, at the end which originally was the cold-junction ; then, by placing the extreme tip of one of the halves successively upon portions of the other half, say at intervals 1 in. apart along its entire length, and applying heat to each of these junctions, to watch the deflections obtained on the milli-voltmeter ; thus proving the non-homogeneous thermoelectric state to exist, by the ability to produce thermocouples, possessing considerable and variable electromotive forces, from two halves of the same nominal material.

Owing to these rapidly changing conditions, whilst in use, of the materials from which the fire-rods are made, the magnitude of the " cold-junction error " is quite an uncertain one ; because the opposite ends of the stems are not likely at any given time when in use to have the same thermoelectric value, and the employment of " compensating leads " and various other ingenious devices provided for eliminating the

cold-junction error, and which add considerably to the expense of installation, do not obviate this very much greater source of error.

There are, however, other matters which give rise to errors of very considerable magnitude, and which are well worth the careful consideration of manufacturers of this class of apparatus, as we have proved them capable of being remedied. We will now endeavour to point them out as clearly as possible.

In those forms of fire-rods which are made so that one element surrounds the other in the form of a tube, two faults in construction frequently show themselves some little time after the stems have been put into use; the first being that the electric weld of the centre wire to the tip of the outer tube is not made of sufficient size, or mechanically strong enough, to withstand the different rate of expansion and contraction between the two metals; the friction of the fire-clay or porcelain insulation between wire and tube being often great enough to hold the wire quite rigid in the upper portions of the tube, so that the extreme tip is gradually forced out from the weld. The second fault is that when the end of the iron tube has got too hot during the electric welding process, the central wire, by reason of its being usually of a lower melting-point than the surrounding tube, partly fuses for some little distance below the weld, and thus becomes spongy and denatured, and gives way at this point in a very short time. Samples showing evidence of these faults are available for inspection, as are also remedies which we have adopted with success, including an improved means of insulating the central wire from the surrounding tube by means of very small fire-clay beads.

In most of the base-metal pyrometry systems, and indeed in other thermoelectric systems as well, no serious care seems to have been taken by manufacturers to ensure that in all the indicating and recording instruments supplied, the ohmic resistance at their terminals shall be of exactly the same value. The absence of this uniformity puts out of the question the obtaining of uniform readings at any given temperature from fire-rods used in connection therewith which have varying lengths or internal resistances.

In one installation which came under our notice the tested terminal resistance of a considerable number of instruments varied from a maximum of 5·3 ohms to a minimum of 2·67 ohms, no two being alike. The result is that although when a definite electromotive force is applied to the terminals of any two of such instruments the readings they give may be alike, what actually happens when measuring temperatures in practice is that, owing to this differing terminal resistance, an identical electromotive force due to temperature, at the tip of a fire-rod of even slight internal resistance, will give different readings on each instrument. Also, when a number of rods are standardized to read correctly upon one instrument kept for that purpose, their readings will be variable upon all others in the installation.

It is a matter therefore of great importance that such instruments should not only be made to give the same indications for given electromotive forces applied to their terminals, which is usually done, but great care should be taken to ensure also that all instruments supplied to any one installation have exactly the same ohmic resistance at their terminals.

The principal source of most of the serious troubles, however, lies in the fact that generally in these systems the terminal resistance of the measuring instruments is made of too low an order. This fault is

responsible for errors in temperature readings of a variable magnitude, quite unsuspected by those using the pyrometers, and brought about by very small variations liable at any time to arise in practical work in the resistances of fire-rods or conducting wires, such as the slightest departure from a perfect electrical contact, whenever this has to be handled by those in charge. A little dust, for instance, may get between contacts at the head of the fire-rods, or between the prongs of a selector switch. Variations in resistance will also occur by the alteration, by even a few inches, in the length of the connecting wires, or even by heat radiating on to some portion of these wires due to a furnace door being opened, or by the wires getting laid across a hot portion of the floor. In fact, any disturbing element which varies the electrical resistance of the external circuit ever so slightly sets up an appreciable error.

It is not at all unusual to find in these installations that the combined resistance of fire-rod, furnace connecting wires, and fixed wiring up to a recorder, is about equal in value to that of the instrument itself, and that an increase of resistance of the connections at any point, of so small a magnitude as 0·12 of an ohm (a quite frequent occurrence with some of the very elaborate connectors supplied), will make a reduction in readings of the order of 18° C.

As this is a matter of considerable importance, we give the following figures, which represent those we have found occurring in practice, during tests upon modern works installations.

	Ohms.
Resistance of a normal 9-ft. fire-rod	0·46
Resistance of furnace leads	0·14
Resistance of fixed wires to recorder	3·00
Making total resistance of external circuit	3·60
Resistance of recorder	3·60
Total resistance of circuit	7·20
Actual electromotive force generated at the tip of the fire-rod, when same is kept constant at 800° C. and cold-junction also constant at 25° C.	35 mv.

If these values be set out upon a sheet of squared paper, so as to form the usual " fall in potential " diagram familiar to electricians, the resulting figure—which expresses graphically the fact that in any electrical circuit the fall in potential along the resistance of any portion of that circuit is proportional to the fall in potential along the resistance of the whole circuit—also illustrates that the initial electromotive force value, as produced at the tip of the fire-rod, falls during the passage of the current along the various resistances of which the circuit is made up, until, when as in this case the recorder resistance equals that of the rest of the circuit, only 50 per cent. of the original electromotive force, or 17·5 millivolts, remains for measurement at the terminals of the recorder.

In order to satisfy requirements, however, the points to which the needle swings are calibrated so as to indicate the temperature at the tip of the fire-rod, that is to say, the movements of the needle are really given the value of $\frac{1}{17·5}$ of 800 degrees, or 45·7 degrees per milli-volt measured by the instrument at this part of its scale.

Now suppose that due to merely a bad connection, such as referred

to above, a strained wire, or any alteration of circuit resistance due to heat, etc., there occurs an increase of resistance of 0·12 ohm in the external circuit; the total resistance will now be 7·32 ohms, and that of stem, leads, wiring, etc., 3·72 ohms, the recorder remaining the same, 3·6 ohms. The fall in electromotive force now proceeds similarly along the circuit, but at the terminals of the instrument only 49·18 per cent. of the original 35 milli-volts, or 17·21 milli-volts, now remains to be measured. Seeing, however, that the instrument still registers at the rate of 45·7 degrees per milli-volt, it will now read 17·21 multiplied by 45·7, or 786·5 degrees, or 13·5° C. lower than before. This result actually occurred during a test under works conditions.

If, however, the resistance of the recorder had been, say, 400 ohms instead of 3·6 ohms, and taking all other values exactly the same as in the above case, the effect of the 0·12 ohm increase in the stem or wiring resistances will be found, on working out the values in the same manner as the last example, to make a difference of only 0·24° C. in the readings of the instrument.

In order to keep this source of error to the lowest possible limit, needlessly heavy wiring from furnaces to recorders has usually to be resorted to, also the position of the recorders is necessarily fixed very near to the furnaces, thus introducing further troubles due to dirt and heat.

The bases of these instruments being very often constructed of wood, heat effects are observed to introduce variations of more than 10° C. in their readings, a further aggravation of this error occurring when the recording chart mechanism is mounted upon this wooden base quite some distance away from the position occupied by the milli-voltmeter itself, so that any warping which does take place causes a direct displacement of the relative positions of needle and chart.

Another point apparently overlooked in the mounting of these instruments on wood bases instead of iron ones is that if when in use they should get placed upon or fixed against any mass of iron (a most likely thing to happen in a steelworks where work of large size is in progress), the readings are at once lowered in value, due to magnetic leakage. Observed errors due to this cause are of the order of 16° C.

In systems which employ a vertical needle in the milli-voltmeter, and especially when ink-dots upon a chart are made by a tubular pen carrying a small wick which transfers ink from a pad attached to the needle depressor, variable readings of the order of 30° C. are set up on either side of the vertical axis of the milli-voltmeter, according as the ink wick is in a moist or nearly dry condition. Moreover, the slightest accident happening to the end of the needle when changing charts is liable to alter the turning moment due to gravity on the needle in the same manner. This liability is not present in the case of a horizontal needle.

In the method of inking the pens just referred to, the depressor pad is apt to get a hollow formed upon its surface at places where a steady temperature is often maintained, and the needle then finds difficulty in disengaging itself from these hollows at any alteration of temperature.

Where chart papers of circular pattern are employed, it often happens that the hole at the centre is not accurately punched, and errors of reading and record due to this cause alone, of 30° C., have been frequently observed during one revolution of the chart.

In some forms of concentric connectors which are used for joining

up the heads of fire-rods to the wiring the central connection piece, along with its surrounding insulation, owing to not being efficiently secured, has a trying habit of working loose and slowly rotating, thus gradually twisting off the centre wire of the flexible leads inside the insulation. This goes on quite unsuspected by the operator, and sets up most puzzling readings, at one time good, at another erroneous.

It may be objected that all the individual errors, liability to which we have mentioned, are but slight ones, and of little importance in a practical system for industrial purposes. This may be so; the facts are, however, that they occur with annoying frequency and also they seldom occur singly, for, on occasions when we have been called upon to investigate variable errors, amounting to some 50° or 100° C., we have found them to be made up of quite a number of small errors due to causes already referred to, each contributing either a plus or minus quota to the larger error.

It is usually objected that a high-resistance instrument is much more costly and much more delicate to construct than one of low resistance which has substantial pivots and control springs. This we admit; but why should we instal a set of apparatus for any purpose which is unreliable, and therefore unsuitable, and likely to be the cause of bad work with consequent loss, thus bringing discredit and careless treatment upon itself, simply because it has the one merit of being robust, when for a little greater first expense and care in installation, by providing suitable protection for high-class instruments, continued good results, and therefore respect and consequent careful treatment by the workmen, is the outcome? This at least has been our experience, and we trust our remarks may not be misunderstood to have been made in any spirit of adverse criticism, but may be received as they have been offered, namely, with a view to help forward and encourage a higher standard of work and appreciation of pyrometry.

In conclusion, I would like to acknowledge the help I have received in these investigations from my assistant, Mr. H. R. S. Johnson, and also to express my thanks to Messrs. Sir W. G. Armstrong, Whitworth, & Co., Ltd., for the courteous facilities afforded me in the presentation of these notes before the Faraday Society.

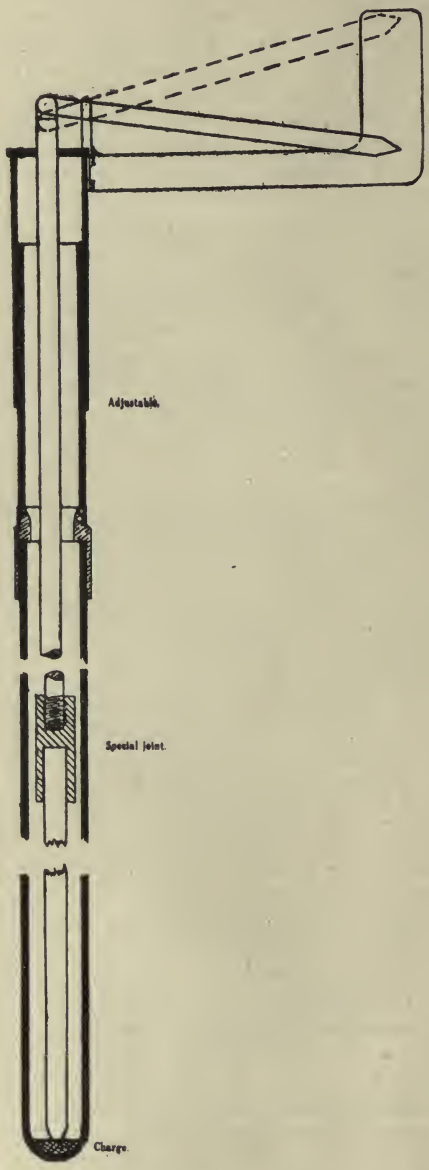
Elswick Works, Newcastle-on-Tyne.

The "Stone" Patent Pyrometer for molten metals was exhibited after the meeting.

Acting in collaboration with Mr. W. R. Barclay, of Sheffield University, and now of the Ministry of Munitions, Mr. Stone devised this simple piece of apparatus for indicating the correct pouring temperature of the special alloys for which an urgent and abnormal demand arose at the outbreak of war. It was primarily intended for use in the training of the additional labour which had to be called in to supplement the skilled men then available in the production of these alloys.

The apparatus, as shown in the illustration, consists of an outer tube of fused silica closed at its lower end, whilst to the upper part is fitted a brass tube made in two parts, telescope fashion, the connection being provided with slots and set screws for exact adjustment of length. Inside the tube is a rod, the lower portion of which is made of fused silica and the upper portion of iron. The top of this latter passes through a

hole in the cap of the metal tube and is then, by means of a pivot, connected to a pointer having its fulcrum on an upstanding portion of the bracket which is secured at right-angles to the brass tube. This bracket



terminates in a quadrant indicator plate with an open-sided bridge piece, up and down which the pointer is free to move.

Placed in the lower end of the silica tube, and of a mass carefully proportioned to allow for expansion, is a small piece of fusible metal of the same class of alloy as the metal for which the apparatus is to be

used, but with the constituents proportioned so that the melting-point corresponds to the temperature at which the metal in the crucible shall be poured. The silica rod rests upon this piece of metal, and when so resting the pointer is in the zero position, as shown in the drawing.

On the outside of the silica tube, that portion which comes into contact with the molten metal in the crucible is coated with a special covering to resist the cutting action of the slag and the reaction of the molten metal.

When the time has arrived for ascertaining whether the metal is ready for pouring, the end of the pyrometer is lowered into the crucible, and when the requisite temperature has been reached, the small piece of metal inside the tube will melt and thus allow the rod to descend by gravity, until its end rests upon the bottom of the tube. In so descending it raises the pointer in the quadrant to the position shown by the dotted lines, thus indicating in a positive manner that the crucible charge is ready for pouring. The pyrometer is then withdrawn from the crucible, and in order to prevent its metal charge from solidifying round the rod, the outer end of the pointer is depressed until it is forced by a spring catch into a recess in the bridge-piece, thus lifting the rod clear of the metal. As soon as the charge has solidified, it is merely necessary to release the pointer and the apparatus is ready for service.

The pyrometers are now being manufactured by Mr. Samuel Platts, scientific instrument maker, 6, Holly Street, Sheffield.

DISCUSSION.

The **Chairman**, in asking for written comments on the papers, said he hoped Mr. Darling would carry on this work and put before the industrial world a practical form of pyrometer utilizing the property he had suggested.

Mr. W. Bowen (Leeds) (*communicated*). Mr. Stone's criticisms of the detail arrangement of base-metal thermocouple pyrometers are concise and valuable. Accepting Mr. Stone's qualification of the causes of trouble as being remediable it is evident that he realizes the outstanding advantages that may follow the use of a well-designed base-metal pyrometer. This attitude towards the base-metal thermocouple is supported by the fact that practically every British pyrometer maker supplies this type of instrument for certain ranges of temperature, the thermocouple of the Hoskins nickel chromium alloys taking the highest place in the scale of temperatures for which base-metals are offered.

In various parts required for renewal and maintenance of a pyrometer interchangeability is undoubtedly important and this is usually provided for by the makers. In order to achieve the maximum advantage in robustness it is usual to make all the thermocouples in one outfit of the same length or resistance. In my experience more than 90 per cent. of base-metal pyrometers employ a thermocouple three feet long, and this length is therefore usually made a standard one.

The demand is much less for interchangeability between different pyrometer outfits and employing thermocouples of different lengths; certainly I should put it at less than 10 per cent., therefore such cases are best treated specially. For such conditions I endorse Mr. Stone's suggestion to make all the milli-voltmeters interchangeable; one such instance has come within

my own experience where, starting from a small number of isolated pyrometer installations the use has extended to almost all departments in a large works; in this case I have advised making all the instruments interchangeable.

As I have indicated above, notwithstanding the relatively large employment of base-metal pyrometers in a few large works, numerically more than 90 per cent. of such instruments are used on installations which only require to be interchangeable on renewals and so forth. If Mr. Stone's proposal were adopted in these cases it would involve reducing all instruments to the sensitivity of the lowest and adding expense from which, in the majority of cases, no material advantage would follow.

With regard to the proportions of the various resistances in the circuit, Mr. Stone's figure for the resistance of the thermocouple fire-rod 9 feet long suggests that two wires were employed in the couple, and in such a case the milli-voltage should have been higher. For instance, if the Hoskins nickel chromium alloys were used, the e.m.f. with the "hot junction" at 800° C. with the "cold-junction" at 25° C., would be about 60 milli-volts. With the same sensitivity in the recorder its resistance would then be 8·7 ohms, reducing the calculated error from 18° C. to 10·5 C. The circular chart recorder has many advantages, and usually such a chart is printed with a small circle in the centre in order to show at a glance if the punching of the centre hole is eccentric. The circular chart has been a great advantage against a strip chart because, in the latter, it is not easy to see if the ruling is parallel with the edge of the chart.

The test for homogeneity of the thermocouple material as described in the paper is fairly well known to pyrometer makers, but cannot be regarded as quantitative because the temperature gradients are much steeper than could exist in a furnace, consequently the effect of small "parasite" e.m.f.'s due to non-homogeneity is, in practice, usually negligible. Certainly it is of no importance at the relatively low temperatures existing at the "cold junction." Mr. Stone is not correct in assuming that the presence of nickel in a thermocouple element will necessarily give rise to parasite e.m.f's. The Hoskins alloys, which employ large percentages of nickel, do not show any such parasite e.m.f.'s.

The demand for a milli-voltmeter of high resistance is much more justified with thermocouples of platinum alloys because of the much higher resistance and larger temperature-resistance coefficients of such thermocouples. In such pyrometers changing the depth of insertion in the furnace makes a large change in resistance, several ohms in a 9 foot thermocouple, therefore high internal resistance in the milli-voltmeter is practically essential.

In conclusion it seems probable that most of the smaller difficulties which Mr. Stone mentions may be attributable to the war, not only because manufacture has been rendered more difficult, but because the experienced staff of the users has been depleted and overworked. Against these troubles may be set the greater robustness and simplicity of the base-metal type of pyrometer and the much lower cost, particularly when considering large numbers of such long thermocouples as are here referred to.

Mr. C. E. Foster (*communicated*): Having devoted a large part of my attention to the design of base-metal pyrometers for the last fourteen years, I can appreciate the value of the criticisms which Mr. Stone makes from the point of view of a user of this class of instrument.

I regret that the wide scope covered by the papers at the meeting did not give time for verbal discussion of Mr. Stone's paper, as I believe that if the users of pyrometers can be enlightened as to the various factors entering into the design of pyrometers, they will be able to make better

use of the instrument as they are to-day and to contribute more effectively to the practical value of future designs. At the risk of a rather long contribution to the written discussion I make these observations.

It will be recognized that the ultimate design of any pyrometer will depend upon the relative importance given to the various desiderata which Mr. Stone enumerates so well in the second paragraph of his paper. For instance, if the greatest importance is given to (1) cheapness of installation then (5) accuracy is likely to be poor. If robustness (3) is considered then (1) cheapness will suffer. If we give prominence to (4) we shall be met by the fact that an automatic recorder is essentially more expensive and complicated than a simple indicator so that considerations (1) and (3) will suffer.

By ruling out of the paper any comparison of the base-metal with any other system Mr. Stone contrasts that instrument with an ideal pyrometer of universal applicability. It will be generally admitted that that ideal pyrometer has yet to be designed.

I should like to see contrasted with Mr. Stone's experience of base-metals an account of rare-metal instruments used to the same extent and under exactly the same conditions. I fancy we should have a somewhat similar but longer list of troubles.

Referring to the figures given as typical of circuit resistance of base-metal systems, a cable resistance of 3 ohms is really surprising and must represent an abnormal arrangement. Taking the average size of cable used in wiring of up-to-date pyrometer systems as at least equal to 16 s.w.g. this resistance would represent a distance of something like 650 feet between the thermocouple and the recorder.

Mr. Stone suggests, as a solution of some of the circuit troubles, a milli-voltmeter of 400 ohms internal resistance. Does he realize that in the present state of milli-voltmeter design the moving forces in such an instrument would be only about one-fiftieth those of the low resistance instrument? The value of these moving forces is the measure of the ability of an instrument to withstand the rough usage which is referred to by Mr. Stone under (3). If elimination of the effect of circuit resistance is the cure and the consequent complication is willingly faced, why not solve the problem at once by using potentiometers instead of milli-voltmeters? The installation would be very little more complicated and the cost of an observer making and recording the average readings would be small compared with the other expenses consequent upon the increased elaboration and upkeep.

I consider that these difficulties are swept aside entirely too easily in the last paragraph but one in this part of the paper. One would almost suspect Mr. Stone of an affection for the "good old times" when we all took for gospel the edicts of the German Reichsanstalt and believed in nothing but the platinum-platinum-rhodium thermocouple with a suspended-coil milli-voltmeter. In those days we purchased a length of such couple wire, fused together at one end, a pair of porcelain tubes and a milli-voltmeter and then proceeded "to work out our own salvation" with a hank of bell wire. The pyrometer was kept carefully in a glass case and only brought out occasionally, attended, with due ceremony, by a sort of high priest of the pyrometers, and, after use, usually retired again minus its porcelain tubes.

This desire for a universal pyrometer is not in harmony with modern industrial progress. The tendency nowadays is to design the pyrometer for a specific job and to allocate it to continuous work on that job. I can assure Mr. Stone that in many large works recently organized, where no tradition

stands in the way, base-metal recording pyrometers are installed in proper recorder houses near enough to the furnace to allow the furnace man to watch the record as it is produced and thus control the firing most intelligently.

However, it is evident that Mr. Stone is really more in sympathy with this tendency to specialization than the first part of his paper suggests, because he has designed a most interesting "fixed-point" apparatus devoted to certain well-defined operations.

I should like to know what happens with this fixed-point instrument if the metal in the crucible is hotter than the correct pouring temperature. Presumably the alloy in the tips of the silica tube would melt before it had reached the temperature of the metal in the crucible and the user would then be unable to tell when his metal had cooled down to the correct pouring temperature. I should also be interested to know how many immersions can be expected before the silica tube fails.

In connection with this particular work on pouring temperatures it has been found that certain base-metal pyrometers are very useful. The Hoskins nickel-chromium thermocouple alloys may be directly inserted into molten non-ferrous metals for the purpose of measuring rapidly the pouring temperatures of these metals. The wires are only alloyed away very slowly so that the cost of this method is small and it has consequently had a very wide application in non-ferrous foundry work.

Mr. G. E. M. Stone (*communicated reply*): I wish to thank Mr. W. Bowen and Mr. C. E. Foster for the interest they have taken in my paper. Coming from their point of view, I much appreciate the observations they have made.

Having for a number of years made the design of thermoelectric pyrometers, including both high and low resistance measuring instruments, my special study, I fully understand the preference shown by manufacturers to provide instruments of low and non-uniform resistance wherever possible, but after much investigation I felt it a duty to take the point of view of the users of this class of apparatus, and to point out clearly some of the annoying difficulties they have to contend with, and which are, as I stated, due to design of apparatus and not to the mode of use.

I fully admit Mr. Bowen's explanation as to the relatively small demand for interchangeability, but think I can assure him that if efforts were made to remove these difficulties, his 10 per cent. minority would soon show a very decided increase; for knowledge that troubles of the kind I referred to exist prevents many firms from increasing their use of pyrometers, and therefore the quality of their work, which is of serious importance at the present time.

The statements made in my paper represent matters as I have been able to investigate them, but I am pleased to have Mr. Bowen's information that a Hoskins alloy has now been produced which does not show parasite e.m.f.'s. I hope it can also show improved freedom from varying crystalline states produced when in use.

I notice that even with the excellent value of 60 milli-volts and slightly improved recorder resistance of 8·7 ohms mentioned by Mr. Bowen, the calculated error under the practical conditions I instanced is stated to be 10·5° C., which I think he will admit still exceeds the limit of permissible error.

Referring to the point raised by both Mr. Bowen and Mr. Foster regarding comparison between base-metal and rare-metal systems, this has been gone into, and although my object in writing the paper was,

as stated, to refer only to lines of possible improvement in base-metal systems, I may perhaps mention that were I at liberty to give details of costs of upkeep, etc., in large installations, a study of results in favour of a rare-metal system employing high and uniform resistance instruments would doubtless occasion considerable surprise.

For explanation of the apparently high cable resistances we frequently find in base-metal installations, may I refer Mr. Foster to paragraph 6 in my paper, for, on consideration, he will recognize therein a line of possible improvement indicated.

With reference to Mr. Foster's further remarks, consideration of actual conditions and requirements of pyrometric control of furnaces preclude the general use of potentiometers. A good furnaceman likes to use his temperature indicator in much the same way as a boiler fireman uses his steam gauge, and especially is it a fact that he likes to be sure that the indications given are correct, his treatment of the apparatus and of his work being found to improve accordingly. Instruments of over 400 ohms resistance have been repeatedly installed for the constant and personal operation of furnacemen in places likely to give evidence of very rough treatment; but, as a result of carefully arranged methods of protection, almost invariable success has been the result.

Regarding the fixed-point instrument shown after the meeting, the question is very naturally asked as to its behaviour when the metal in the crucible is hotter than the correct pouring temperature. This instrument was designed, as Mr. Foster rightly suggests, for a special and very definite purpose.

Certain alloys were urgently required at the outbreak of war, and the most rapid method of manufacture then available was to employ sets of crucible furnaces and workmen situate at a number of works quite distinct from each other, which up to then had been almost exclusively employed in melting metals of a varied and generally lower pouring temperature than the new alloys demanded. Some standard of uniformity had therefore to be adopted.

Various pyrometric methods were tried and considered. The temperature was too high for the ordinary thermocouple. Difficulty was found with optical and radiation methods unless skilled operators were present. The directly inserted base-metal method mentioned by Mr. Foster, although attractive, had to be excluded on account of liability to a slight alloying of the thermocouple elements with the contents of the crucible.

In the end this fixed-point instrument was evolved, and tried with success. The special feature, of the charge inside the silica tube being of the same class of alloy as the metal to be melted in the crucible, ensured that should a breakage occur, no foreign constituent enters the melt.

One of the chief troubles in producing the special alloys required was to get the workmen, mostly unused to such high temperatures, to allow their furnaces to attain the required heat, and it was seldom or never that fault had to be found for exceeding that temperature.

As regards the life of the silica tubes, as they have been almost always broken by the workmen, due to some accident when the pyrometer was not in use, it has been difficult to obtain reliable data as to the exact number of immersions under fair conditions, but notwithstanding this, owing to the highly increased value of the special alloys when poured at correct temperature, the users consider that the cost of upkeep repays itself.

EXHIBITS.

Instruments or Furnaces were Exhibited by

The Automatic Electric Furnaces, Ltd.
The Cambridge Scientific Instrument Company, Ltd.
The Foster Instrument Company.
Messrs. Hadfields, Ltd.
Mr. Robert W. Paul.
Messrs. Siemens Bros. & Co., Ltd.
Mr. G. E. M. Stone (see p. 151).
Mr. Henry Watkins

Mr. S. A. Main described the exhibits shown by Messrs. Hadfields, Limited.

Northrup Chart.—Illustrating the lack of knowledge of the properties of matter at high temperatures; the first requirement in further exploration of these high-temperatures regions being a good pyrometer.

Large Temperature Chart.—Showing the range of temperature from the absolute zero to the highest known temperature, that of the surface of the sun. Also the most important metallurgical temperatures, including the principal melting- and freezing-points. Shows the position of the metallurgist in the temperature scheme.

Apparatus.

Brown Control Pyrometer.—Shown in use controlling the temperature of an electric furnace at 800° C.

Goggles of Special "Akopos" Glass.—For avoiding eye-strain, by suppression of the ultra-violet rays, when viewing high-temperature furnaces, and to enable a better ocular estimate of the temperature than with the usual smoked or cobalt blue glass.

Calibration of Pyrometers.—Demonstration of simple methods of checking optical and thermoelectric pyrometers. For the former a Harker furnace is used, temperatures well over 2,000° C. being readily obtainable.

Various Accessories devised and exhibited by the Research Department of Messrs. Hadfields, Ltd., Sheffield.—For use in connection with pyrometers, including:

Battery and control box for optical pyrometers.

Simple switchboard on the lines of a telephone switchboard, for interconnecting each of several furnaces with any one of a number of pyrometers.

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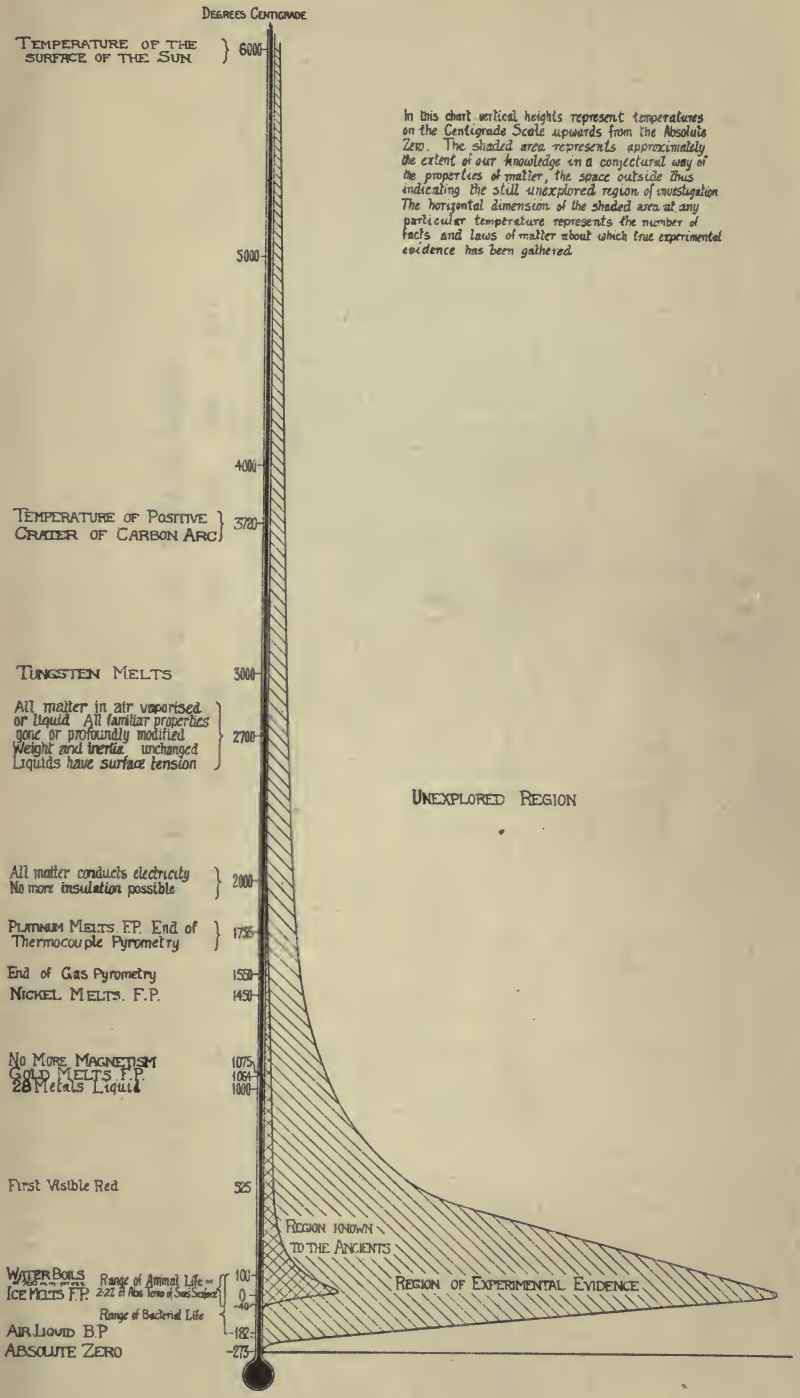
RELATION BETWEEN TEMPERATURE AND SCIENTIFIC INVESTIGATION

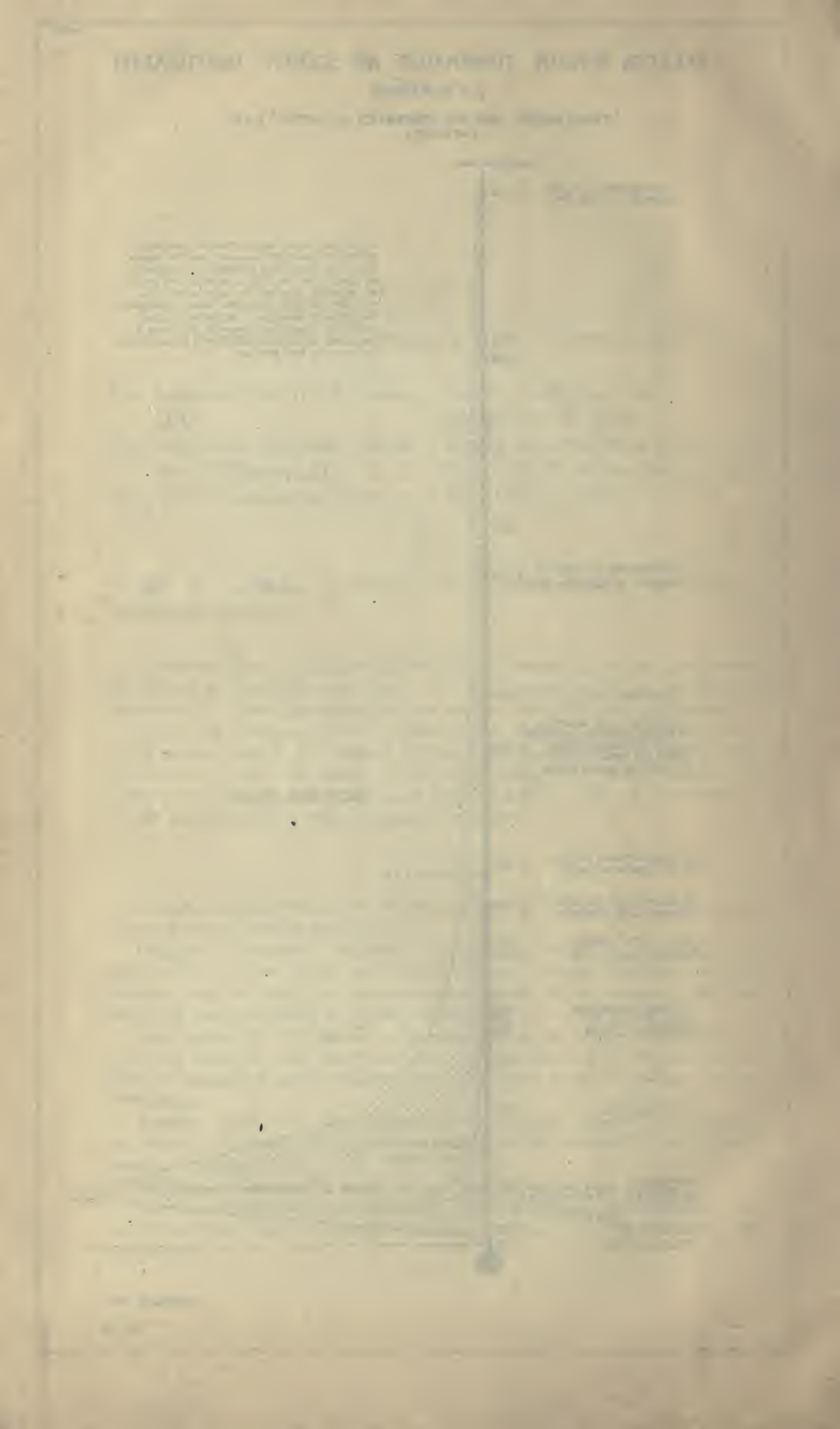
E. F. NORTHRUP

"TEMPERATURE AND THE PROPERTIES OF MATTER" 1912
(REVISED)


DEGREES CENTIGRADE
TEMPERATURE OF THE SURFACE OF THE SUN
6000
5000
4000
TEMPERATURE OF POSITIVE CRATER OF CARBON ARC
3720
TUNGSTEN MELTS
3000
All matter in air vaporised or liquid All familiar properties gone or profoundly modified Weight and inertia unchanged Liquids have surface tension
2700
All matter conducts electricity No more insulation possible
2000
PLATINUM MELTS F.P. End of Thermocouple Pyrometry
1735
End of Gas Pyrometry
1550
NICKEL MELTS. F.P.
1450
No More Magnetism
1075
GOLD MELTS F.P.
1064
28 Metals Liquid
1000
First Visible Red
525
WATER BOILS 760 m.m. press
100
ICE MELTS F.P.
0
Range of Animal Life = 2.22 of Abs. Terms of Cent. Scale
-40
Range of Bacterial Life
AIR LIQUID B.P
-182
ABSOLUTE ZERO
-273
In this chart vertical heights represent temperatures on the Centigrade Scale upwards from the Absolute Zero. The shaded area represents approximately the extent of our knowledge in a conjectural way of the properties of matter, the space outside thus indicating the still unexplored region of investigation The horizontal dimension of the shaded area at any particular temperature represents the number of facts and laws of matter about which true experimental evidence has been gathered
UNEXPLORED REGION
REGION KNOWN TO THE ANCIENTS
REGION OF EXPERIMENTAL EVIDENCE

HADFIELDS LTD

MAY 1916



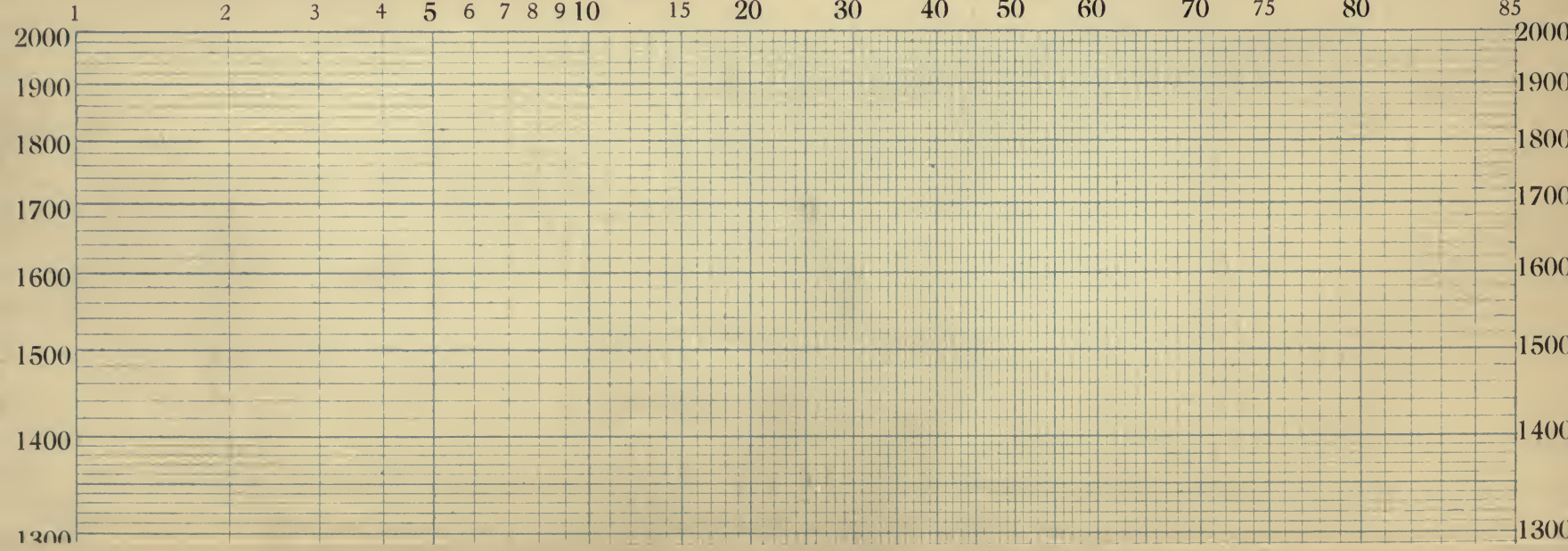
"MAIN" CALIBRATION CHART.

OPTICAL PYROMETER No

DATE

REMARKS

ANGLE of Analyser in DEGREES.



"Main" calibration chart, for facilitating calibration of optical pyrometers. This is a specially ruled chart, on which the calibration line, instead of being of the usual curved form, is a perfectly straight line; serving also as a check on the proper adjustment of the instrument and facilitates extrapolation to higher temperatures by simply producing the straight calibration line, thus avoiding the very complicated calculations otherwise necessary.

Mr. H. L. Heathcote exhibited two forms of optical pyrometer in which liquid in hermetically sealed, glass-ended cells was employed to absorb the "coloured" rays. Each cell of the non-adjustable form (stereo-pyrometer) sufficed to just absorb all the coloured rays emitted up to a certain temperature. If the temperature of the body exceeded that point, the body became visible through the cell in question. In the adjustable type (pyromike) the cell had rubber sides, and by means of a screw-head the length, and therefore the absorptive power of the column of liquid, could be increased or decreased. This instrument gave a very open scale and a range of from 250° to 400° C. The accuracy under favourable circumstances was within 5°. Neither form was a substitute for the excellent instruments shown by other demonstrators, but, like the hand camera, it had a field of usefulness which was not in any way impaired by the superiority of the studio camera.

BIBLIOGRAPHY ON PYROMETERS.

CONTRIBUTED BY SIR ROBERT HADFIELD, F.R.S.

Summary of Bibliography.

DESCRIPTION	PAGE	DESCRIPTION	PAGE
Pamphlets, Papers, and Cuttings	160	Patents (U.S.A.)	169
Patents (British)	168	Books	170

(*a*) Pamphlets, (*b*) Papers, (*c*) Cuttings (dated).

Date.			Title.	Author.	Publication.	Country.	Description.
—	—	1886	Mesures pyrométriques à hautes températures	Lauth et Vogt	Bulletin de la Société chimique	France	Extract
—	January	1887	De la mesure des températures élevées par les couples thermo-électriques	Le Chatelier	Journal de Physique	France	Extract
—	—	1888	Die Pyrometer : Eine Kritik der bisher Construirten höheren Temperaturmesser	Bolz, C. H.	—	Germany	Pamphlet
26	January	1889	Optical Pyrometers	Mésure et Nouel	La Nature	France	Extract
11	October	1890	Pyrometry Data	Howe, H. M.	Engineering & Mining Journal	U.S.A.	Extract
—	November	1891	Murrie's Patent Pyrometers ..	Jas. Murrie & Co.	—	Great Britain	Catalogue
10	April	1892	Optical Pyrometer	H. le Chatelier	L'Industrie électrique	France	Extract
24	May	1892	Measurement of High Temperatures	Roberts-Austen	Inst. Civil Engineers	Great Britain	Pamphlet

1	May	1892	Optical Measurement of High Temperatures	H. le Chatelier	Journal de Physique	France	Extract
17	May	1893	The Recording Pyrometer ..	W. C. Roberts-Austen	Iron & Steel Inst.	Great Britain	Pamphlet
22	February	1894	The Uehling and Steinbart Pyrometer	—	Iron Age	Great Britain	Extract
24	August	1894	The Pneumatic Pyrometer ..	Henry Morton	Engineering	Great Britain	Cutting
—	—	1894	Platinum Pyrometers	H. L. Callendar	Iron & Steel Inst.	Great Britain	Paper
21	February	1895	Mésure and Nouel Optical Pyrometer	F. E. Thompson	Iron Age	U.S.A.	Cutting
29	October	1896	The Pneumatic Pyrometer ..	—	Iron Age	U.S.A.	Cutting
—	—	1897	Seger Cones	—	—	U.S.A.	Leaflet
10	March	1899	Measuring Extreme Temperatures	H. L. Callendar	Royal Institution	Great Britain	Paper
15	May	1899	The Brown Pyrometers	—	Bulletin Am. I.S.A.	U.S.A.	Cutting
—	December	1899	Colour Temperatures of Heated Steel	Maunsel White and F. W. Taylor	A.S.M.E.	U.S.A.	Paper
26	January	1900	The Pneumatic Pyrometer and Autographic Recording Gauge	—	Engineer	Great Britain	Cutting
19	March	1900	A Quartz Thermometer for High Temperatures	M. Defour	—	France	Extract
—	April	1900	Industrial Pyrometry	E. Ducretet	—	France	Pamphlet
29	December	1900	A New Recording Air Pyrometer	W. H. Bristol	Mech. Engineer	Great Britain	Cutting
—	—	1900	Measurement of High Temperatures by Thermoelectric Couple	A. Hill	Journal West Scot. I.S.I.	Great Britain	Paper
—	September	1901	Pyrometers for Measurement of Temperatures	Baird and Tatlock	—	Great Britain	Pamphlet
—	—	1901	Le Chatelier's Pyrometer ..	Holborn and Wien	—	Germany	Pamphlet
15	February	1902	A New Pyrometer	H. Wanner	Stahl und Eisen	Germany	Paper
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